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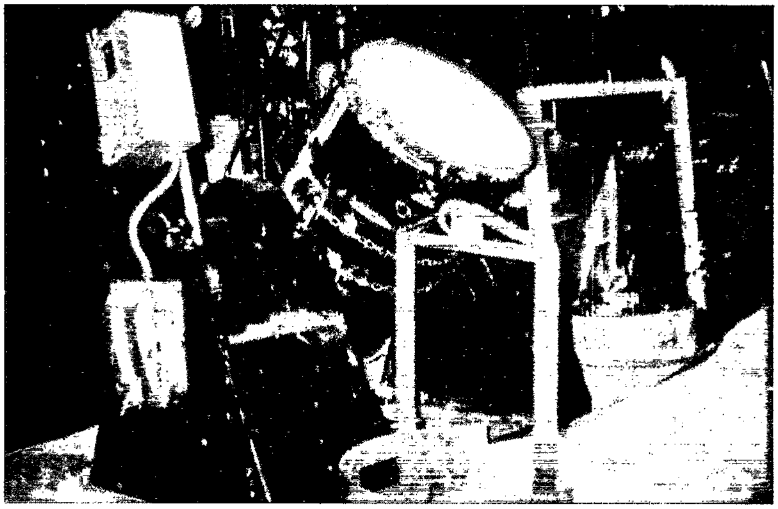
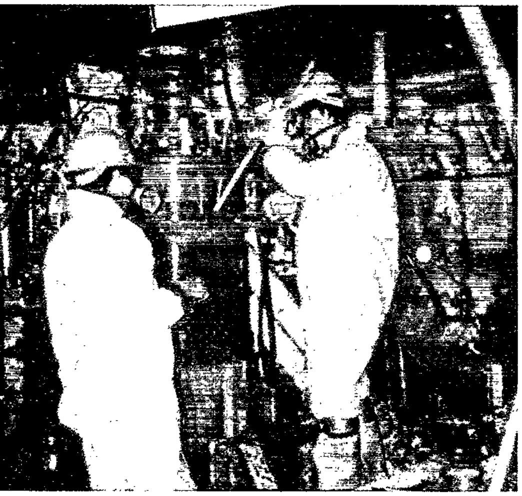
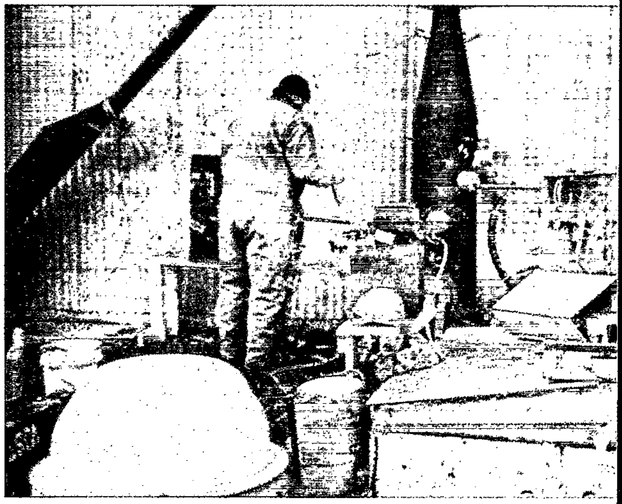
Babcock & Wilcox Cyclone Furnace Vitrification Technology

Applications Analysis Report







SITE

SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

EPA/540/AR-92/017
August 1992

Babcock & Wilcox Cyclone Furnace Vitrification Technology

Applications Analysis Report

Risk Reduction Engineering Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Notice

The information in this document has been funded by the U.S. Environmental Protection Agency (EPA) under the auspices of the Superfund Innovative Technology Evaluation (SITE) Program under Contract No. 68-C0-0048 to Science Applications International Corporation (SAIC). It has been subjected to the Agency's peer and administrative review, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use.

Foreword

The Superfund Innovative Technology Evaluation (SITE) Program was authorized in the 1986 Superfund Amendments. The Program is a joint effort between EPA's Office of Research and Development and Office of Solid Waste and Emergency Response. The purpose of the program is to enhance the development of hazardous waste treatment technologies necessary for implementing new cleanup standards that require greater reliance on permanent remedies. This is accomplished by performing technology demonstrations designed to provide engineering and economic data on selected technologies.

This project consists of an analysis of the Babcock & Wilcox (B&W) Cyclone Furnace Vitrification Technology. The Demonstration Test took place at the Babcock & Wilcox Research and Development pilot facility located in Alliance, Ohio. The goals of the study, summarized in this Applications Analysis Report, are: 1) to evaluate the technical effectiveness and economics of this technology relative to its ability to treat soils contaminated with heavy metals, radionuclides, and organics; and 2) to establish the potential applicability of the process to other wastes and Superfund sites. The primary technical objective of this project is to determine the ability of the process to produce a non-leachable vitrified material that immobilizes heavy metals and radionuclides. The process is also being evaluated for its ability to destroy any organic contaminants present in the Synthetic Soil Matrix (SSM).

Additional copies of this report may be obtained at no charge from the EPA's Center for Environmental Research Information, 26 West Martin Luther King Drive, Cincinnati, Ohio 45268, using the EPA document number found on the report's front cover. Once this supply is exhausted, copies can be purchased from the National Technical Information Service, Ravensworth Building, Springfield, Virginia, 22161 (703) 487-4650. Reference copies will be available in the Hazardous Waste Collection at EPA libraries.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

Abstract

This document is an evaluation of the performance of the Babcock & Wilcox (B&W) Cyclone Furnace Vitrification Technology and its applicability as a treatment technique for soils contaminated with heavy metals, radionuclides, and organics. Both the technical and economic aspects of the technology were examined.

A demonstration of the B&W vitrification technology was conducted in the fall of 1991 using B&W's pilot-scale unit located at its Alliance Research Center in Alliance, Ohio. Operational data and sampling and analysis information were carefully compiled to establish a database against which other available data, as well as the vendor's claims for the technology, could be compared and evaluated. Conclusions concerning the technology's suitability for use in immobilizing metal and radionuclides in soils as well as destroying organic contaminants were reached. Extrapolations regarding applications to different contaminants and soil types were made.

The following conclusions were derived primarily from the Demonstration Test results and supported by other available data: (1) the treated soil did not leach any metals at levels above the regulatory limits; (2) the process achieved a Destruction and Removal Efficiency (DRE) of greater than 99.99 percent for each Principal Organic Hazardous Constituent (POHC); (3) particulate emissions were below the regulatory limit; (4) the non-volatile metals were retained in the slag; and (5) simulated radionuclides were immobilized.

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Abbreviations

AAR	Applications Analysis Report
ANS	American Nuclear Society
ARAR	Applicable or Relevant and Appropriate Requirements
ASTM	American Society for Testing and Materials
B&W	Babcock and Wilcox
CAA	Clean Air Act
CEM	Continuous Emission Monitor
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPR	Cardiopulmonary Resuscitation
CWA	Clean Water Act
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DRE	Destruction and Removal Efficiency
EPA	Environmental Protection Agency
gr/dscf	grains per dry standard cubic foot
gpm	gallons per minute
MSW	Municipal Solid Waste
NPDES	National Pollutant Discharge Elimination System
NO_x	Nitrogen Oxides
O_2	Oxygen
ORD	Office of Research and Development
OSHA	Occupational Safety and Health Act
OSWER	Office of Solid Waste and Emergency Response
PIC	Products of Incomplete Combustion
POHC	Principal Organic Hazardous Constituent
ppm	parts per million
POTW	Publicly-Owned Treatment Works
psig	pounds per square inch gauge
RCRA	Resource Conservation and Recovery Act
RREL	Risk Reduction Engineering Laboratory
SARA	Superfund Amendments & Reauthorization Act
scf	standard cubic feet
scfm	standard cubic feet per minute
SDWA	Safe Drinking Water Act
SITE	Superfund Innovative Technology Evaluation
SSM	Synthetic Soil Matrix
SVOC	Semi-Volatile Organic Compounds
TCLP	Toxicity Characteristic Leaching Procedure

Abbreviations (Continued)

TER	Technology Evaluation Report
THC	Total Hydrocarbons
tph	tons per hour
tpd	tons per day
TSD	Treatment, Storage, and Disposal
VOC	Volatile Organic Compounds
VOST	Volatile Organic Sampling Train

Acknowledgments

This report was prepared under the direction and coordination of Ms. Laurel Staley, EPA Superfund Innovative Technology Evaluation (SITE) Program Manager in the Risk Reduction Engineering Laboratory (RREL), Cincinnati, Ohio. EPA-RREL contributors and reviewers for this report were Robert Stenburg, Randy Parker, and Kim Lisa Kreiton. Babcock and Wilcox contributors and reviewers were Jean Czuczwa, Dan Rowley, Hamid Farzan, William Musiol, James Warchol, and Stanley Vecci.

This report was prepared for EPA's SITE Program by the Technology Evaluation Division of Science Applications International Corporation (SAIC) in Cincinnati, Ohio for the U.S. EPA under Contract No. 68-C0-0048. The Work Assignment Manager for this project was Ms. Margaret M. Groeber.

Section 1

Executive Summary

1.1 *Introduction*

This report summarizes the findings of an evaluation of the Cyclone Furnace Vitrification Technology developed by Babcock & Wilcox (B&W). The study was conducted under the Superfund Innovative Technology Evaluation (SITE) Program. A Demonstration Test of the technology was performed by U.S. Environmental Protection Agency (EPA) as part of this program. The results of this test and supporting data from other testing performed by B&W constitute the basis for this report.

1.2 *Conclusions*

A number of conclusions may be drawn from the evaluation of this innovative technology. The most extensive data were obtained during the SITE Demonstration Test. Data from other testing activities have been evaluated in relation to SITE Program objectives. The conclusions drawn are:

- The slag produced complied with Toxicity Characteristic Leaching Procedure (TCLP) regulatory requirements for cadmium, chromium, and lead.

- Ninety-four percent of the non-combustible portion of the soil was incorporated within the slag.

- Most of the non-volatile metals remained in the slag. On the average, the percentages for chromium, strontium, and zirconium retained in the slag were 76, 88, and 97 percent, respectively. Metals which partitioned to the flue gas were captured by the baghouse.

- A volume reduction of 29 percent from the feed Synthetic Soil Matrix (SSM) to the slag was achieved on a dry weight basis.

- Destruction and Removal Efficiencies (DREs) for each Principal Organic Hazardous Constituent (POHC) were greater than 99.99 percent.

- An average of 0.001 grains per dry standard cubic foot (gr/dscf) of particulate (corrected to 7 percent O_2) was emitted, which is less than the Resources Conservation and Recovery Act (RCRA) regulatory limit of 0.08 gr/dscf at 7 percent O_2.

- The simulated radionuclides were immobilized within the slag according to American Nuclear Society Method 16.1.

- The process formed products of incomplete combustion; however, concentrations were in the parts per trillion range.

- The cost to remediate 20,000 tons of contaminated soil using a 3.3-ton per hour cyclone furnace vitrification system is estimated at $465 per ton if the system is online 80 percent of the time or $529 per ton if the system is online 60 percent of the time.

1.3 *Results*

The objectives of this Applications Analysis are to assess the ability of the process to comply with Applicable or Relevant and Appropriate Requirements (ARARs) and to estimate the cost of using this technology to remediate a Superfund site. This analysis includes determining if the cyclone furnace can produce a non-leachable vitrified material that immobilizes a significant percentage of the metals, particularly chromium. It also includes determining DREs and air emissions from the process. Table 1 lists the unit's performance as it relates to ARARs.

Table 1. B&W SITE Demonstration Test Results and Potential Incineration ARARs

Contaminant	Average	Range	ARARs
TCLP (mg/L)			
SSM			
Cadmium	49.9	31.0 - 75.3	1.0
Chromium	2.64	1.30 - 4.32	5.0
Lead	97.3	72.2 - 128	5.0
Slag			
Cadmium	0.12	0.03 - 0.30	1.0
Chromium	0.22	0.07 - 0.81	5.0
Lead	0.31	<0.25 - 0.66	5.0
DRE (%)			
Anthracene	>99.997	>99.996 ->99.997	99.99
Dimethylphthalate	>99.998	>99.998 - >99.998	99.99
Stack Emissions			
Particulate matter (gr/dscf at 7% O_2)	0.0008	0.003 - 0.0014	0.08
Nitrogen oxides (NO_x, ppm)	a	310 - 435	b
Carbon monoxide (ppm)	a	4.8 - >54.1	<100
Total hydrocarbons (ppm)	a	<5.9 - 18.2	<20
Cadmium (lb/hr)	3.27×10^{-6}	9.4×10^{-6} - 1.5×10^{-4}	c
Chromium (lb/hr)	2.70×10^{-5}	2.1×10^{-5} - 1.9×10^{-4}	c
Lead (lb/hr)	1.88×10^{-5}	4.8×10^{-5} - 7.1×10^{-4}	c

a Average concentration for each run is presented in Appendix C. Average concentration for the entire Demonstration was not calculated.

b Allowable emissions limits established on a case-by-case basis as per the requirements of the Clean Air Act.

c Less than those established by EPA Guidance on Metal Emissions from Hazardous Waste Incinerators.

Other results regarding the ratio of slag-to-flyash, metal partitioning, volume reduction, and characterization of feed soil and baghouse solids are also addressed.

A full discussion of the SITE Demonstration Test results is included in Appendix C and supported in Appendix D, Case Studies.

Section 2

Introduction

2.1 *The SITE Program*

In 1986, the U.S. Environmental Protection Agency (EPA) Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) established the Superfund Innovative Technology Evaluation (SITE) Program to promote the development and use of innovative technologies to clean up Superfund sites across the country. Now in its fifth year, SITE is helping to provide the treatment technologies necessary to implement new Federal and State cleanup standards aimed at permanent remedies rather than quick fixes. The SITE Program is composed of three major elements: the Demonstration Program, the Emerging Technologies Program, and the Measurement and Monitoring Technologies Program.

The major focus has been on the Demonstration Program, which is designed to provide engineering and cost data for selected technologies. To date, the Demonstration Program projects have not involved funding for technology developers. EPA and developers participating in the program share the cost of the demonstration. Developers are responsible for demonstrating their innovative systems at chosen sites, usually Superfund sites. The EPA is responsible for sampling, analyzing, and evaluating all test results. The result is an assessment of the technology's performance, reliability, and costs. This information is used in conjunction with other data to select the most appropriate technologies for the cleanup of Superfund sites.

Developers of innovative technologies apply to the Demonstration Program by responding to EPA's annual solicitation. EPA also accepts proposals any time a developer has a Superfund waste treatment project scheduled. To qualify for the program, a new technology must be at the pilot- or full- scale and offer some advantage over existing technologies. Mobile technologies are of particular interest to EPA.

Once EPA has accepted a proposal, EPA and the developer work with the EPA regional offices and state agencies to identify a site containing waste suitable for testing the capabilities of the technology. EPA prepares a detailed sampling and analysis plan designed to evaluate the technology thoroughly and to ensure that the resulting data are reliable. The duration of a demonstration varies from a few days to several months, depending on the length of time and quantity of waste needed to assess the technology. After the completion of a technology demonstration, EPA prepares two reports, which are explained in more detail in the following paragraphs. Ultimately, the Demonstration Program leads to an analysis of the technology's overall applicability to Superfund problems.

The second principal element of the SITE Program is the Emerging Technologies Program, which fosters the further investigation and development of treatment technologies that are still at the laboratory scale. Successful validation of these technologies could lead to the development of a system ready for field demonstration and participation in the Demonstration Program. The third component of the SITE Program, the Measurement and Monitoring Technologies Program, provides assistance in the development and demonstration of innovative technologies to characterize Superfund sites better.

2.2 *SITE Program Reports*

The analysis of technologies participating in the Demonstration Program is contained in two documents: the Technology Evaluation Report (TER) and the Applications Analysis Report (AAR). The TER contains a comprehensive description of the demonstration sponsored by the SITE program and its results. It gives detailed descriptions of the technology, the waste used for the demonstration, sampling and analysis during the test, the data generated, and the quality assurance program.

The scope of the AAR is broader than the TER and encompasses estimation of the Superfund applications and costs of a technology based on all available data. This report compiles and summarizes the results of the SITE demonstration, the vendor's design and test data, and other laboratory and field applications of the technology. It discusses the advantages, disadvantages, and limitations of the technology.

Costs of the technology for different applications are estimated based on available data on pilot- and full-scale applications. The AAR discusses the factors, such as site and waste characteristics, that have a major impact on costs and performance.

The amount of available data for the evaluation of an innovative technology varies widely. Data may be limited to laboratory tests on synthetic waste or may include performance data on actual wastes treated at the pilot- or full-scale level. In addition, there are limits to conclusions regarding Superfund applications that can be drawn from a single field demonstration. A successful field demonstration does not necessarily ensure that a technology will be widely applicable or fully developed to the commercial scale. The AAR attempts to synthesize whatever information is available and draw reasonable conclusions. This document is very useful to those considering a technology for Superfund cleanups and represents a critical step in the development and commercialization of the treatment technology.

2.3 *Key Contacts*

For more information on the demonstration of the B&W technology, please contact:

1. EPA Project Manager for the SITE Demonstration Test:

   Ms. Laurel Staley
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Section 3

Technology Applications Analysis

3.1 Introduction

This section addresses the applicability of the Babcock & Wilcox (B&W) Cyclone Furnace Vitrification Technology to various contaminated soil matrices where heavy metals, radionuclides, and various organics are the pollutants of primary interest. Recommendations are based on the results obtained from the SITE demonstration as well as additional data from B&W. The results of the demonstration provide the most extensive database, conclusions on the technology's effectiveness, and its applicability to other potential cleanups. Additional information on the B&W technology, including a brief process description, vendor's claims, and a summary of the demonstration results are provided in Appendices A through C.

3.2 Conclusions

Soil contaminants are either immobilized, thermally destroyed (oxidized), or volatilized in B&W's cyclone furnace. It successfully produced a non-leachable, vitrified slag that immobilized heavy metals and radionuclides. The technology also destroyed the organic contaminants present in the soil.

A review of the Demonstration Test indicates the following results:

- The slag produced complied with Toxicity Characteristic Leaching Procedure (TCLP) regulatory requirements for cadmium, chromium, and lead.

- Ninety-four percent of the non-combustible portion of the soil was incorporated within the slag.

- Most of the non-volatile metals remained in the slag. On the average, the percentages for chromium, strontium, and zirconium retained in the slag were 76, 88, and 97 percent, respectively. Metals which partitioned to the flue gas were captured by the baghouse.

- The volume of slag produced was 29 percent smaller than the feed soil on a dry weight basis.

- Destruction and Removal Efficiencies (DREs) for Semi-Volatile Organic Compounds (SVOCs) were greater than 99.99 percent.

- An average of 0.001 grains per dry standard cubic foot (gr/dscf) of particulate corrected to 7 percent O_2 was emitted, which is less than the Resource Conservation and Recovery Act (RCRA) regulatory limit of 0.08 gr/dscf at 7 percent O_2.

- The simulated radionuclides (strontium, zirconium, and bismuth) were immobilized within the slag according to American Nuclear Society (ANS) Method 16.1.

- The process formed products of incomplete combustion; however, concentrations were in the parts per trillion range.

3.3 Technology Evaluation

The 6-million Btu/hr pilot-scale furnace used in this demonstration is a scaled-down version of the B&W commercial coal combustion cyclone furnace. This unit employs high temperatures to vitrify high inorganic hazardous wastes (e.g., soils) that may also contain organic constituents. The technology was demonstrated using a Synthetic Soil Matrix (SSM) provided by the EPA Risk Reduction Engineering Laboratory (RREL) in Edison, New Jersey. The contaminants used to spike the SSM were chosen in order to produce a feed with contamination problems similar to those encountered at

Superfund sites, Department of Defense (DOD) facilities, and Department of Energy (DOE) facilities. The SSM is a well characterized, clean material used for technology evaluations which has been spiked with heavy metals, SVOCs, and simulated radionuclides [1].

Simulated radionuclides are non-radioactive metals, the behavior of which in the cyclone furnace will simulate true radionuclide species. The simulated radionuclides selected were strontium, bismuth, and zirconium. Bismuth was used as a surrogate for volatile radionuclides found at DOE/DOD sites such as cesium (cold cesium was originally proposed but found to be excessively expensive). Cold strontium was used as a surrogate for radioactive strontium (the cold version of the radionuclide is the best possible surrogate). Zirconium was considered an excellent surrogate for radioactive thorium and uranium from the standpoint of both volatility and chemical behavior.

Data regarding simulated radionuclides are suspect because the method has not been validated for these metals. Since the method accuracy and precision are not well quantified, the data are used for informational purposes only.

Table 2 is a summary of the spiked components and their concentrations in the SSM. The chosen spikes allow for proper evaluation of the technology without risk to personnel safety and limit the generation of hazardous products.

Table 2. Total Concentrations of Spiked Components Measured in the SSM

	Concentration (mg/kg)	
Analyte	Average	Range
Heavy Metals		
Cadmium	1260	1000-1800
Chromium	4350	3800-4680
Lead	6410	3880-7510
Simulated Radionuclides		
Bismuth	4180	2810-7210
Strontium	3720	3300-4100
Zirconium	4070	3660-5000
Organic Compounds		
Anthracene	4710	3300-7800
Dimethyl-phthalate	8340	4800-10000

The following paragraphs present information available on the B&W cyclone furnace and its performance and summarize observations and conclusions on the process as they relate to the SITE demonstration.

3.3.1 Slag Characteristics

3.3.1.1 Leachability

Ninety-four percent of the non-combustible portion of the feed is transformed from loosely packed soil to a brittle, glass-like slag. The remaining 6 percent becomes particulate matter in the flue gas. Table 3 summarizes the concentrations of the spiked components in the resultant slag.

Table 3. Total Concentrations of Spiked Components Measured in the Slag

	Concentration (mg/kg)	
Analyte	Average	Range
Heavy Metals		
Cadmium	106	62.7-177
Chromium	1610	922-2110
Lead	1760	1270-2420
Simulated Radionuclides		
Bismuth	730	522-949
Strontium	3210	1890-3830
Zirconium	3640	2080-4420
Organic Compounds		
Anthracene	<0.24[a]	(0.04)[b]-<0.34
Dimethyl-phthalate	<3.89[a]	<0.33-11[c]

a If a result was undetected, the detection limit was used in calculations for averages. This represents worst case scenario.

b Estimated value above instrument detection limit but below method quantitation limit.

c The analysis of the field blank yielded similar values indicating the sample may have been contaminated.

B&W claims its vitrification technology produces a non-leachable, vitrified slag. For the demonstration, TCLPs were performed on both the feed SSM and the slag. The SSM was tested to determine the leachability of heavy metals prior to treatment. The slag was tested to demonstrate compliance with TCLP regulatory limits. The leachabilities of the heavy metals in the feed soil and the slag are summarized in Table 4, which includes TCLP regulatory levels.

Table 4. **TCLP Results from B&W SITE Demonstration (mg/L)**

	Cadmium	Chromium	Lead
Regulatory Limits	1.0	5.0	5.0
SSM			
Average	49.9	2.64	97.3
Range[a]	31.0-75.3	1.30-4.32	72.2-128
Slag			
Average	<0.12[b]	0.22	<0.31[b]
Range[a]	<0.03-0.30	0.07-0.81	<0.25-0.66

a Range represents low-to-high values of the 27 samples taken over the Demonstration period.

b If a result was undetected, the detection limit was used in calculations for averages. This represents worst case scenario.

TCLP results for the slag indicate the cyclone furnace can treat metal-contaminated soils to the extent that the leachate from the resultant slag will comply with the allowable limits. When TCLPs were performed on the feed, the concentrations of lead and cadmium in the leachate were greater than the regulatory limits; however, this was not the case for chromium. It is not known why chromium remains relatively fixed in the soil. TCLP results from previous testing by B&W (refer to Appendix D - Case Studies) also indicated the leachate contained concentrations of chromium less than the regulatory limit. For the demonstration, chromium concentrations were triple that of levels from these previous tests; however, the leachate still did not exceed the regulatory limit.

The cyclone vitrification process not only produces a slag that complies with TCLP requirements, but decreases the leachability of metals in the slag. This decrease in leachability is caused by the physical/chemical properties of the SSM changing as it passes through the cyclone furnace.

The leachability of the simulated radionuclides from the slag was determined according to ANS 16.1 - "American National Standard Measurement of the Leachability of Solidified Low-Level Radioactive Wastes by a Short-Term Test Procedure." This method provides a measure of the release of simulated radionuclides from the slag at ambient temperatures. A leachability index of six or greater indicates these metals are immobilized within the slag. In order to account for the irregular shape of the slag material, the method used to quantify the external surface area of the slag was modified.

Although all other equations and data reduction procedures remain the same, the method has not been validated for the material in question and accuracy and precision are not well quantified; therefore the data are suspect. The slag's leachability index for bismuth, strontium, and zirconium were 13.4, 13.1, and 8.7, respectively. These results indicate the simulated radionuclides are immobilized.

3.3.1.2 Volume Reduction

The vitrification process reduces the volume of the feed SSM. Approximately 20 percent of the SSM is made up of materials that combust as they pass through the cyclone furnace. These materials include carbonates, sulfates, and organics. Their combustion results in a decrease in volume. Percent volume reductions were determined by comparing the volume of dry SSM introduced to the furnace to the volume of dry slag produced. The average volume reduction was 29 percent. Bulk densities of the SSM and slag are almost equivalent; therefore any volume reduction is the result of this combustion, not a change in bulk density.

3.3.2 Metals Partitioning

As the SSM goes through the cyclone furnace, metals partition to either the flyash or the slag. Their fate depends on the relative volatility of the metal. The non-volatile metals such as chromium, strontium, and zirconium remain mainly in the slag. The more volatile metals such as bismuth, cadmium, and lead tend to partition to the flue gas where they are collected by the baghouse. During the demonstration, over 75 percent (by weight) of the chromium in the SSM was incorporated in the vitrified slag. This percent of retention is consistent with retentions obtained during previous tests (refer to Appendix D - Case Studies). In addition, approximately 88 and 97 percent of the strontium and zirconium, respectively, remained in the slag. The more volatile bismuth, cadmium, and lead had lower retention (27, 12, and 29 percent, respectively).

Almost all of the total mass of metals which partition to the flue gas are captured by the baghouse. A very small portion of the mass of metals pass through the baghouse and out the stack. However, as long as these levels do not exceed the furnace's permit limits (as determined by a site-specific risk assessment), no significant changes to emission treatment need be employed. Table 5 summarizes the distribution of the metals during the demonstration.

Results from the TCLP analysis of the baghouse solids indicate the TCLP limits for cadmium and chromium were exceeded. The baghouse solids therefore require disposal as a hazardous waste. During the demonstration, 6,000 pounds of SSM were treated and approximately 150 pounds of baghouse solids were collected. This is a

Table 5. Metals Partitioning from the Cyclone Vitrification Process (%)

Metal	Slag	Baghouse	Stack gas
Bismuth[a]			
Average	26.8	73.1	<0.08[b]
Range	25.7-28.4	71.6-74.3	<0.06-0.11
Cadmium			
Average	11.8	88.1	0.04
Range	11.3-12.7	87.3-88.8	0.01-0.17
Chromium			
Average	75.8	24.2	0.04
Range	73.7-79.3	20.7-26.3	0.01-0.11
Lead			
Average	29.2	70.8	0.05
Range	24.3-33.2	66.8-75.7	0.01-0.13
Strontium[a]			
Average	87.8	12.2	0.01
Range	85.0-89.3	10.7-15.0	0.003-0.03
Zirconium[a]			
Average	96.5	3.5	0.02
Range	95.7-97.4	2.6-4.3	0.02-0.03

a These are included for informational purposes only since the accuracy and precision of these data are suspect.

b If a result was undetected, the detection limit was used in calculations for averages. This represents worst case scenario.

significant decrease in the amount of material requiring disposal as hazardous waste.

Modifications have been proposed that would recirculate the baghouse solids through the furnace, allowing the system additional opportunities to trap the metals within the slag. This modification may eliminate the need to dispose of or treat the flyash as a hazardous waste.

3.3.3 Air Emissions

3.3.3.1 Particulate

During the Demonstration Test, particulate emissions were measured directly after exiting the furnace outlet (prior to the air pollution control equipment) and at the stack (after the baghouse). Emissions out of the stack easily met the RCRA emissions limit of 0.08 gr/dscf corrected to 7 percent oxygen (O_2). Table 6 summarizes particulate data from the Demonstration Test. The table includes both measured values and values corrected to 7 percent O_2. The correction factor of 14 ÷ (21 - percent O_2) takes into account the dilution factor in the stack gas caused by excess air needed for combustion.

Table 6. Summary of Particulate Emissions

Run No.	Location	Concentration (gr/dscf) Measured	Concentration (gr/dscf) 7%O_2	Rate (lb/h)
1	Furnace Outlet	0.858	0.765	5.57
	Stack	0.0016	0.0014	0.017
2	Furnace Outlet	0.864	0.817	5.76
	Stack	0.0009	0.0008	0.009
3	Furnace Outlet	1.058	0.837	6.89
	Stack	0.0003	0.0003	0.004

By comparing the particulate emission rate from the stack test at the furnace outlet with the amount of slag produced per hour by the cyclone furnace, the slag-to-flyash ratio was determined for each run. The average slag to flyash ratio from the Demonstration was 13.7. In addition to providing a relationship from which baghouse solids production can be estimated, this result demonstrates the cyclone furnace is capable of treating the contaminated soil without experiencing major losses as particulate emissions.

3.3.3.2 DRE

The measure used to evaluate organic destruction during the Demonstration Test is the DRE. This parameter is determined by analyzing the concentration of the Principal Organic Hazardous Constituent (POHC) in the feed SSM and the stack gas. RCRA regulations define DRE for a given POHC as follows:

$$DRE\ (\%) = \frac{W_{in} - W_{out}}{W_{in}} \times 100\%$$

Where:

W_{in} = Mass feed rate of the POHC of interest in the waste stream feed

W_{out} = Mass emission rate of the same POHC present in exhaust emissions prior to release to the atmosphere

POHCs identified for the demonstration were anthracene and dimethylphthalate. These compounds were selected as representative stable compounds for the purpose of evaluating the furnace's ability to destroy organic compounds.

The cyclone furnace achieved DREs greater than 99.99 percent for both of these organics. This indicates the cyclone furnace is capable of achieving the DREs required for a RCRA hazardous waste incinerator (99.99 percent). Because the concentrations of both anthracene and dimethylphthalate in the stack gas were below detection limits, these results do not indicate the maximum DREs the cyclone furnace is capable of achieving. Measurable quantities of POHCs were expected in the stack gas since high levels of POHCs were spiked in the SSM (refer to Table 2) and their corresponding detection limits are low. This indicates the furnace obtained better-than-expected results.

For the Demonstration Test, the gas temperature exiting the cyclone barrel was approximately 3000°F, while the gas leaving the furnace had a temperature of over 2000°F and a 2 second residence time. Similar operating conditions are projected for the commercial-scale system. Because anthracene and dimethylphthalate are relatively difficult organics to destroy, it is projected that the commercial-scale cyclone furnace will be capable of achieving DREs of 99.99 percent or greater for all or nearly all organics.

3.3.3.3 Products of Incomplete Combustion (PICs)

Volatile Organic Compound (VOC) emissions which reflect the formation of PICs, were detected in the parts per trillion range for the cyclone furnace. Organic compounds spiked in the SSM were non-chlorinated; therefore, PICs from this process should also be non-chlorinated. However, several chlorinated compounds were detected.

In order to account for these chlorinated compounds, three samples of the feed SSM were analyzed for trace levels of chlorine. The chlorine levels ranged from <0.01 percent to 0.03 percent. These trace amounts probably resulted in the formation of chlorinated VOCs.

Higher concentrations of chlorinated VOCs may be detected in the stack gas if a feed soil contains chlorinated compounds; however, it is expected concentrations would be very low. Soils contaminated with chlorinated organics would also form hydrogen chloride (HCl) gas from the cyclone vitrification process which would have to be controlled by a scrubber.

3.3.3.4 Continuous Emission Monitors (CEMs)

CEMs were used to measure nitrogen oxides (NO_x), carbon monoxide (CO), total hydrocarbons (THC), carbon dioxide (CO_2), and O_2 emissions during the Demonstration Test.

NO_x emissions are generally a result of the combustion process rather than the nitrogen content of the feed. The NO_x concentrations from the demonstration were relatively low; however, a unit larger than the pilot system may emit significant levels of NO_x, which may make it a major source under the Clean Air Act. Allowable emissions of NO_x will be established on a case-by-case basis.

CO and THC emissions were relatively low and indicate relatively complete combustion occurs within the cyclone furnace, as also indicated by the low PIC concentrations (refer to Section 3.3.3.3). Results from the demonstration do not indicate the cyclone furnace will have difficulty in meeting the RCRA limit of 100 parts per million (ppm) for CO. THC emissions from the demonstration, however, were close to the RCRA limit of 20 ppm. Careful monitoring of THC emissions from the furnace will be required in order for the unit to operate in compliance.

CO_2 and O_2 in the stack gas were analyzed by CEMs and Orsat analysis. Values obtained from both analyses compared favorably with one another. O_2 levels in the stack gas indicate excess air values from the combustion process. Operating at low excess air values may result in incomplete combustion; too high values may reduce combustion temperatures or increase fuel requirements. O_2 values obtained reflect typical excess air values for a natural gas-fired furnace.

3.3.4 Quench Water

Slag exiting the cyclone furnace is cooled and collected in a tank filled with quench water. Quench water samples collected before and after each run were analyzed to determine if any of the metals present in the slag or infusible matter leached into the quench water. Analyses of the quench water from the baseline run and the three test runs indicated minimal increases in the concentrations of certain metals during the test runs. Concentrations of cadmium, chromium, lead, and strontium were so close to the detection limits that it cannot be determined if the process causes any increase/decrease in concentrations. Concentrations of bismuth and zirconium remained below detection limits throughout the testing period.

Quench water samples collected before and after the second and third test runs were analyzed for anthracene and dimethyl phthalate to determine whether these chemicals leached into the quench water. Concentrations of both chemicals remained below method quantitation limits throughout both test runs.

When the Demonstration Test was complete, the quench water was found to be suitable for discharge to a sanitary sewer and was disposed of in accordance with the terms of B&W's wastewater discharge agreement with its local Publicly-Owned Treatment Works (POTW). It is projected that the quench water from the commercial-scale system will be suitable for discharge to a sanitary sewer, but this must be determined on a site-specific basis.

Water that came in contact with the SSM (wash and rinse water from demonstration equipment cleanup) was collected, stored apart from other wastes, and disposed of as a hazardous waste. The nature of the wash water and rinse water will be site-specific. It may be a hazardous or radioactive waste at some sites; at other sites it may be suitable for discharge to a sanitary sewer.

In the commercial-scale cyclone furnace soil vitrification system, the slag quench water, wash water, and rinse water will only occasionally discharge. It is projected that the commercial-scale system will continuously discharge water from a quench tower, which will use water to cool the flue gas (the pilot-scale system did not include a quench tower). The water from the quench tower should be suitable for discharge to a sanitary sewer.

3.4 Ranges of Site Characteristics Suitable for the Technology

3.4.1 Site Selection

The current pilot-scale cyclone furnace is not transportable; however, it is projected the commercial-scale unit will be able to be moved from site to site. The following discussion of suitable site characteristics applies only to the commercial-scale unit.

Although the geological features of a site have an effect on the equipment that may be used within the contaminated area, normally the cyclone furnace may be erected within the confines of the contaminated area or positioned so that the waste can be easily transported to the furnace. Ultimately, in order for the furnace to be used onsite, the characteristics of the site must allow for the construction of a pad and the assembly of the system.

3.4.2 Surface, Subsurface, and Clearance Requirements

A level graded area capable of supporting a pad holding the equipment is needed. The foundation must be able to support the weight of the cyclone furnace (at least 20 tons), heat exchanger, water quench tower, feed system, baghouse, and scrubber. The total weight of all system components is expected to be at least 200 tons. The site must be cleared to allow construction and access to the facility.

3.4.3 Topographical Characteristics

The topographical characteristics of the site should be suitable for the assembly of the furnace and all ancillary equipment, such as the baghouse, scrubber, water quench tower, heat exchanger, and feed system. A small building must be constructed to house the controls for the system. The lime required by the scrubber should be stored in this building or in a separate facility.

3.4.4 Site Area Requirements

A minimum area of 3000 square feet is required for the cyclone furnace vitrification system and the pad used to support the system. Additionally, separate areas should be provided where wastes generated during treatment may be stored and where feed preparation activities can proceed prior to treatment. Since the furnace can be configured into any position, the shape of the site is inconsequential except when it limits access to the equipment.

3.4.5 Climate Characteristics

This treatment technology may be used in a broad range of different climates. Although prolonged periods of freezing temperatures may interfere with soil excavation, these temperatures would not affect the operation of the furnace itself.

3.4.6 Geological Characteristics

Generally, any site that is sufficiently stable to handle the weight of the furnace facility is suitable for this technology. However, this B&W cyclone furnace should not be employed in areas with landslide potential, volcanic activity, and fragile geological formations that may be disturbed by heavy loads or vibrational stress.

3.4.7 Utility Requirements

In order to operate the cyclone furnace, access must be available to electrical power, water, compressed air, and natural gas supplies. In order to install and operate the furnace, a 3-phase electrical source capable of providing 440 volts at 140 amps is required. To maintain a sufficient supply of water for the quench tower and scrubber, a minimum water flowrate of 40 gallons per minute (gpm) is needed. The baghouse will require approximately 85 standard cubic feet per minute (scfm) of compressed air at 60 to 100 pounds per square inch gauge pressure (psig). Natural gas must be provided to serve as a supplemental fuel in the cyclone furnace, which consumes approximately 100,000 standard cubic feet (scf) of natural gas per hour of operation. Oil and coal may also be used as supplemental fuels.

3.4.8 Size of Operation

The feed rate for the pilot-scale cyclone furnace soil vitrification system utilized during the SITE demonstration was approximately 170 lb/hr of contaminated soil. The pilot-scale system occupied an area measuring approximately 30 feet long by 30 feet wide.

The projected soil feed rate for the commercial-scale cyclone furnace soil vitrification system is 80 tons per day (tpd), or approximately 3.3 tons per hour (tph). The layout of the commercial-scale system may be adjusted somewhat to conform to an optimum facility design plan. The area required for onsite construction of the system will vary with the configuration, but it will require at least 2400 square feet.

3.5 Applicable Media

The B&W cyclone furnace can be used to treat soils, sludges, liquids, and slurries contaminated with hazardous inorganic and organic constituents, low level radioactive solid wastes, or a combination of the two. The pollutant concentrations which may be treated by this technology are constrained by the characteristics (i.e., volatility, mobility, etc.) of the individual pollutants and the ability of the furnace to destroy or immobilize the different pollutants.

The Demonstration Test indicated that the furnace was capable of destroying 99.99 percent of the SVOCs spiked within the SSM (as demonstrated by DREs) and immobilizing approximately 12 percent of the cadmium, over 75 percent of the chromium, and approximately 29 percent of the lead present within the feed. Since TCLP analyses of the slag demonstrate acceptable leachability characteristics, these metals are most likely trapped within the slag. Metals analyses of the baghouse solids indicate that the remainder of the metals are volatilized and collected with the particulate by the baghouse.

Simulated radionuclides (bismuth, strontium, and zirconium) from the feed were also immobilized in the slag during the Demonstration Test. Approximately 27 percent of the bismuth, 88 percent of the strontium, and 97 percent of the zirconium were immobilized in the slag. Simulated radionuclides not contained in the slag were primarily recovered in the baghouse solids. Because actual radionuclides are expected to behave similarly, this technology can be used to treat radioactive soils to prevent the migration of radionuclides from a site. Following treatment, the slag and the baghouse solids will still be radioactive, but it is projected that the slag will be nonleachable.

3.6 Regulatory Requirements

Operation of the B&W Cyclone Vitrification Furnace Technology for treatment of contaminated soil requires compliance with certain Federal, state, and local regulatory standards and guidelines. Section 121 of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) requires that, subject to specified exceptions, remedial actions must be undertaken in compliance with Applicable or Relevant and Appropriate Requirements (ARARs), Federal laws, and more stringent promulgated state laws (in response to release or threats of releases of hazardous substances, pollutants, or contaminants) as necessary to protect human health and the environment.

The ARARs which must be followed in treating contaminated media onsite are outlined in the Interim Guidance on Compliance with ARAR, Federal Register, Vol. 52, pp. 32496 et seq. These are:

- Performance, Design, or Action-Specific Requirements. Examples include RCRA incineration standards and Clean Water Act (CWA) pretreatment standards for discharge to POTWs. These requirements are triggered by the particular remedial activity selected to clean a site.
- Ambient/Chemical-Specific Requirements. These set health-risk-based concentration limits based on pollutants and contaminants, e.g., emission limits and ambient air quality standards. The most stringent ARAR must be complied with.
- Locational Requirements. These set restrictions on activities because of site locations and environs.

Deployment of the B&W cyclone furnace will be affected by three main levels of regulation:

- Federal EPA air and water pollution regulations
- State air and water pollution regulations
- Local regulations, particularly Air Quality Management District requirements

These regulations govern the operation of all technologies. Other Federal, state, and local regulations are discussed in detail in the following paragraphs as they apply to the performance, emissions, and residues evaluated from measurements taken during the Demonstration Test.

3.6.1 Federal Regulations

3.6.1.1 Clean Air Act (CAA)

The CAA establishes primary and secondary ambient air quality standards for the protection of public health and emission limitations for certain hazardous air pollutants. Because the cyclone furnace has the potential to emit pollutants which are presently regulated under the CAA, notably CO and NO_x, operators of this system must pay particular attention to the control of these emissions and compliance with the ambient air quality standards. Other regulated emissions may also be produced, depending on the waste feed. During the Demonstration Test, particulate matter, CO, and THC from the stack gas were monitored relative to their effect on the emission limits stipulated under 40 CFR 264. NO_x emissions were also evaluated.

3.6.1.2 CERCLA

CERCLA of 1980 as amended by the Superfund Amendments and Reauthorization Act (SARA) of 1986 provides for Federal funding to respond to releases of hazardous substances to air, water, and land. Section 121 of SARA, Cleanup Standards, states a strong statutory preference for remedies that are highly reliable and provide long-term protection. It strongly recommends that remedial action use onsite treatment that "...permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances." In addition, general factors which must be addressed by CERCLA remedial actions include:

- Overall protection of human health and the environment
- Compliance with ARARs
- Long-term effectiveness and permanence
- Reduction of toxicity, mobility, or volume
- Short-term effectiveness
- Implementability
- Cost
- State acceptance
- Community acceptance

The ability of the B&W cyclone furnace to destroy the majority of the organic contaminants originally present in the feed, as demonstrated by DREs of 99.99 percent or greater, indicates the cyclone furnace is capable of "permanently and significantly" reducing the threat posed by the organic compounds. TCLP analyses of the vitrified slag demonstrated that the cyclone furnace is capable of immobilizing heavy metal contaminants within the slag in the short-term. However, the long-term effectiveness and permanence of these results were not evaluated as part of this project. It is anticipated, however, that the heavy metals will be immobilized within the treated soil.

The short-term effectiveness of the B&W process may be evaluated by examining analytical data obtained from the stack gas and stack gas solids. Since the stack emissions are well below the emission limits stipulated by 40 CFR for particulates, CO, and THC, the data indicate that the cyclone furnace is highly reliable in respect to the regulated emissions of concern.

Except for soil-bearing capacity requirements, very few site characteristics can restrict the implementation of this system. Unfortunately, the system is not easily or quickly assembled or disassembled. Thus the cyclone furnace is better suited for facilities where ongoing treatment is required rather than for facilities where short-term or small-scale treatment is required.

This technology may be used to treat media contaminated with metals, radionuclides, and organics which are not amenable to treatment using traditional techniques. If the cyclone furnace were applied to such media, the organics would be destroyed. A portion of the metals and radionuclides would be immobilized in the slag; the remainder would be contained in the baghouse solids. Both the slag and the baghouse solids would be radioactive and the baghouse solids would likely be hazardous. It is projected that the metals and radionuclides in the slag would be nonleachable since the slag generated during the SITE demonstration was nonleachable. The slag would be considered nonhazardous according to CERCLA requirements.

3.6.1.3 RCRA

RCRA is the primary Federal legislation governing hazardous waste activities. Under RCRA, various incineration performance standards are established. Although a RCRA permit is not required, the cyclone furnace must meet all of its substantive requirements. However, administrative RCRA requirements such as reporting and recordkeeping are not applicable for onsite action.

Subtitle C of RCRA contains requirements for generation, transport, treatment, storage, and disposal of hazardous waste. Compliance with these requirements is mandatory for CERCLA sites producing hazardous waste onsite.

Two potentially hazardous waste streams, the baghouse solids and the treated slag, are produced by the B&W cyclone furnace. Since a limited potential exists for the heavy metals to leach from the slag, as demonstrated by TCLP data, the flyash from the baghouse constitutes the primary hazardous waste stream produced by this process. This material is contaminated with metals which volatilized or oxidized to form fumes or fine particulates during the treatment process. These metal fumes and particles were removed from the gas stream by the baghouse.

In order to maintain compliance with RCRA, sites employing the cyclone furnace must obtain an EPA generator identification number and observe storage requirements stipulated under 40 CFR 262. Alternatively, a Part B Treatment, Storage, and Disposal (TSD) permit of interim status may be obtained. Invariably, a hazardous waste manifest must accompany offsite shipment of waste and transport must comply with Federal Department of Transportation hazardous waste transportation regulations. Without exception, the receiving TSD facility must be permitted and in compliance with RCRA standards.

The technology or treatment standards applicable to the media produced by the B&W furnace (vitrified slag and baghouse solids) will be determined by the characteristics of the material treated and the waste generated. The RCRA land disposal restrictions (40 CFR 268) preclude the land disposal of hazardous wastes which fail to meet the stipulated treatment standards. Wastes which do not meet these standards must receive additional treatment to bring the wastes into compliance with the standards prior to land disposal, unless a variance is granted. The amount of baghouse solids requiring treatment or disposal may be eliminated if they are recycled through the furnace. This modification has been proposed by B&W although it has not been tested.

3.6.1.4 CWA

The CWA regulates direct discharges to surface water through the National Pollutant Discharge Elimination System (NPDES) regulations. These regulations require point-source discharges of wastewater to meet established water quality standards. The discharge of wastewater to the sanitary sewer requires a discharge permit or, at least, concurrence from state and local regulatory authorities that the wastewater is in compliance with regulatory limits.

During the SITE demonstration, the water used to quench the molten slag produced by the cyclone furnace was disposed of in accordance with the terms of B&W's wastewater discharge agreement with its local POTW. The wash water from decontamination and rinse water from demonstration equipment cleanups was collected, stored separate from other wastes, and disposed of as a hazardous waste. The nature of the wash and rinse water will be site-specific; it may be a hazardous waste at some sites. In the commercial-scale system, the slag quench water, wash water, and rinse water will create only occasional discharges. The water from the quench tower will be discharged continuously during operation and should be suitable for discharge to a sanitary sewer.

3.6.1.5 Safe Drinking Water Act (SDWA)

The SDWA establishes primary and secondary national drinking water standards. CERCLA refers to these standards and Section 121(d)(2) explicitly mentions two of these standards for surface water or groundwater - Maximum Contaminant Levels (MCLs) and Federal Water Quality Criteria. Alternate Concentration Limits may be used when conditions of Section 121 (d)(2)(B) are met and cleanup to MCLs or other protective levels is not practicable. Included in these sections is guidance on how these requirements may be applied to Superfund remedial actions. The guidance, which is based on Federal requirements and policies, may be superseded by more stringent promulgated state requirements, resulting in the application of even stricter standards than those specified in Federal regulations.

3.6.1.6 Atomic Energy Act (AEA)

Radioactive material treatment, storage, and disposal are regulated under the AEA. For commercial and most federal facilities, the Nuclear Regulatory Commission (NRC) maintains the regulatory framework under which use of radioactive material is controlled. For DOE facilities, standards for the control of radioactive material are established under a series of DOE Orders. Most NRC regulations are not directly applied to DOE facilities, since both agencies were founded under the auspices of the AEA. However, some NRC regulations, particularly in disposal of certain wastes, are directly applicable to DOE operations.

Operation of the B&W furnace for treatment of radioactive materials at a non-DOE facility must be specifically authorized under a license issued by the NRC, mandating compliance with the safety and health standards contained in 10 CFR 20. The license application will define the conditions under which the furnace would be operated to ensure health and safety protection of the workers, the public, and the environment. At a DOE facility, the comparable requirements for general radiation protection will apply, although no license document would be required.

Disposal of the treatment residuals from the furnace would be regulated under 10 CFR 61 or DOE Order 5820.2A, depending of whether it is at a DOE facility. Under either set of requirements, a defined upper concentration level has been established for near surface disposal of certain radionuclides.

Certain regulations of the EPA also apply to some forms of radioactive waste disposal. In general, the EPA radioactivity standards would not apply to the B&W furnace, unless it is used to treat high-level waste or wastes from a uranium or thorium mill tailing site.

If treatment residues contain both RCRA regulated constituents and radioactive material, they would be classified as mixed waste. Since there are no currently operating mixed waste disposal facilities, any mixed waste resulting from operation of the furnace would have to meet the RCRA land disposal regulations standards such that it could be stored for the time required to develop an acceptable disposal facility.

3.6.2 State and Local Regulations

Compliance with ARARs may require meeting state standards that are more stringent than Federal standards or that are the controlling standards in the case of non-CERCLA treatment activities. Several types of state and local regulations which may affect operation of the B&W cyclone furnace are cited below:

- Permitting requirements for construction/operation
- Limitations on emission levels
- Nuisance rules

3.7 Personnel Issues

3.7.1 Training

Since all personnel involved with sampling or working close to the furnace will be required to wear respiratory protection, 40 hours of Occupational Safety and Health Act (OSHA) training covering Personal Protective Equipment Application, Safety and Health, Emergency Response Procedures, and Quality Assurance/Quality Control are required. Additional training addressing the site activities, procedures, monitoring, and equipment associated with the technology is also recommended. Personnel should also be briefed when new operations are planned, work practices change, or if the site or environmental conditions change.

3.7.2 Health and Safety

Personnel should be instructed on the potential hazards associated with the operation of the cyclone furnace, recommended safe work practices, and standard emergency plans and procedures. Health and Safety Training covering the potential hazards and provisions for exposure, monitoring, and the use and care of personal protective equipment should be required. When appropriate, workers should have medical exams. Medical exams are particularly appropriate if the cyclone furnace is being used for the remediation of radioactive media. All workers should be routinely monitored for exposure to radiation. Health and safety monitoring and incident reports should be routinely filed and records of occupational illnesses and injuries (OSHA Forms 102 and 200) should be maintained. Audits ensuring compliance with the health and safety plan should be carried out.

Proper personal protective equipment should be available and properly utilized by all onsite personnel. Different levels of personal protection will be required based on the potential hazard associated with the site and the work activities.

Site monitoring should be conducted to identify the extent of hazards and to document exposures at the site. The monitoring results should be maintained and posted.

3.7.3 Emergency Response

In the event of an accident, illness, explosion, hazardous situation at the site, or intentional acts of harm, assistance should be immediately sought from the local emergency response teams and first aid or decontamination should be employed where appropriate. To ensure a timely response in the case of an emergency, workers should review the evacuation plan, firefighting procedures, cardiopulmonary resuscitation (CPR) techniques, and emergency decontamination procedures before operating the system. Fire extinguishers, spill cleanup kits, alarms, evacuation vehicles, and an extensive first aid kit should be onsite at all times.

For sites with radioactive media, bioassay urine samples should be collected whenever an intake above allowable limits may have occurred.

3.8 References

1. Procedures Manual for Preparation of Synthetic Soils Matrix (SSM 019) Samples for B&W SITE Program. Prepared by Foster Wheeler Enviresponse, Inc. for the U.S. Environmental Protection Agency, September 1991.

Section 4
Economic Analysis

4.1 *Introduction*

The primary purpose of this economic analysis is to estimate costs (not including profits) for a commercial treatment system utilizing the B&W cyclone furnace vitrification process. This analysis is based on the results of a SITE demonstration which utilized a pilot-scale cyclone furnace vitrification system. The pilot-scale unit operated at a feed rate of 170 lbs/hr of contaminated soil and utilized energy at a rate of 5 million Btu/hr. It is projected the commercial unit will be capable of treating approximately 3.3 tons per hour (tph) of contaminated soil and will require an energy input of 100 million Btu/hr. The daily feed rate for the pilot-scale system was approximately 2 tons per day (tpd), while it is projected the commercial system will be capable of treating 80 tpd.

4.2 *Conclusions*

The commercial-scale cyclone furnace vitrification system proposed by B&W appears to be applicable to the remediation of soils and other solid wastes contaminated with organics, metals, and radionuclides. Treatment costs appear to be competitive with other available technologies. The cost to remediate 20,000 tons of contaminated soil using a 3.3 tph cyclone furnace vitrification system is estimated at $465 per ton if the system is online 80 percent of the time or $529 per ton if the system is online 60 percent of the time. Projected unit costs for a smaller site (less than 20,000 tons of contaminated soil) are slightly higher; projected unit costs for a larger site are slightly lower.

4.3 *Issues and Assumptions*

Because the B&W cyclone furnace vitrification process appears to be capable of effectively treating soils contaminated with organics, metals, and radionuclides, it is considered potentially applicable to the remediation of DOE and DOD sites as well as typical Superfund sites. In the following economic analysis, the costs associated with this technology are calculated based on the treatment of 20,000 tons of contaminated soil. This basis was chosen because a small to medium DOE or DOD site may have approximately 20,000 tons of contaminated soil suitable for treatment by cyclone furnace vitrification. Approximately 3 tons of contaminated soil were treated during the SITE demonstration.

Costs which are assumed to be the obligation of the responsible party or site owner have been omitted from this cost estimate and are indicated by a line (---) in all tables.

Important assumptions regarding operating conditions and task responsibilities that could significantly affect the cost estimate results are presented in the following paragraphs.

4.3.1 Costs Excluded from Estimate

The cost estimates presented are representative of the charges typically assessed to the client by the vendor but do not include profit.

Many other actual or potential costs were not included as part of this estimate. These costs were omitted because site-specific engineering designs beyond the scope of this SITE project would be required to determine those costs. As a result, certain functions were assumed to be the obligation of the responsible party or site owner and were not included in this estimate.

Costs such as preliminary site preparation, permits, regulatory requirements, initiation of monitoring programs, waste disposal, sampling and analyses, and post-treatment site cleanup and restoration are considered to be the responsible party's (or site owner's) obligation and are not included. These costs tend to be site-specific and it is left to the reader to perform calculations relevant to each specific case. Whenever possible, applicable information is provided on these topics so the reader may perform calculations to obtain relevant economic data.

4.3.2 Maximizing Treatment Rate

Factors limiting the treatment rate include the feed rate and the online percentage. Increasing the feed rate and/or the online percentage can reduce the unit treatment cost. Increasing the feed rate of the commercial unit beyond 3.3 tph, however, may result in less effective reduction of contaminants.

4.3.3 Utilities

To support the operation of the cyclone furnace vitrification system, a site must have clean water available at a flow rate of at least 40 gpm. The majority of this water (34 gpm) will be used in the water quench tower to cool the flue gas. The remainder of the water will be used in the scrubber and in other miscellaneous onsite applications such as cleaning and rinsing.

A natural gas source and the required piping must be available and accessible to accommodate a natural gas usage of approximately 100,000 cubic feet per hour at standard conditions (60°F and 30 inches of mercury). The natural gas will serve as a supplemental fuel for the cyclone furnace. Alternatively, provisions may be made for the use of oil or coal as a supplemental fuel.

Electrical power is required for the operation of the fan, the baghouse, the scrubber, and many smaller pieces of equipment. The baghouse also requires compressed air, which must be supplied at a pressure of 60 to 100 pounds per square inch gauge (psig) and a flow rate of at least 85 standard cubic feet per minute (scfm).

For these cost calculations, it is assumed the site will support all of these requirements. The cost of preparing a site to meet these requirements can be high and is not included in this analysis.

4.3.4 Operating Times

It is assumed the treatment operations will be conducted 24 hours a day, 5 days a week. It is further assumed site preparation, assembly, shakedown and testing, and disassembly operations will be conducted 12 hours a day, 5 days a week. Excavation activities for site preparation will be concurrent with treatment (and may be concurrent with assembly and shakedown and testing as well). Assembly, shakedown and testing, and disassembly are assumed to require 6 weeks, 6 weeks, and 3 weeks, respectively. Except where noted, these calculations are based on the treatment of a total of 20,000 tons of waste using a 3.3 tph system.

4.3.5 Labor Requirements

Treatment operations for a typical shift are assumed to require ten workers: four feed operators, two maintenance operators, and four system operators. Each shift is assumed to be 8 hours long.

4.3.6 Capital Costs

Capital costs for equipment consist of the cost of the furnace and additional equipment such as a heat exchanger, a water quench tower, a feed system, a baghouse, and a scrubber.

4.3.7 Equipment and Fixed Costs

Annualized equipment cost and costs that are estimated as percentages of equipment costs on an annual basis have been prorated for the duration of time that the equipment is onsite. The costs for equipment, contingency, insurance, and taxes accrue during assembly, shakedown and testing, treatment, and disassembly; scheduled maintenance costs accrue during treatment only.

4.4 Basis of Economic Analysis

The cost analysis was prepared by breaking down the overall cost into 12 categories. The categories, some of which do not have costs associated with them for this particular technology, are:

- Site preparation costs
- Permitting and regulatory costs
- Equipment costs
- Startup and fixed costs
- Labor costs
- Supplies costs
- Consumables costs
- Effluent treatment and disposal costs
- Residuals and waste shipping, handling, and transport costs
- Analytical costs
- Facility modification, repair, and replacement costs
- Site demobilization costs

The 12 cost factors examined as they apply to the B&W cyclone furnace vitrification process, along with the assumptions employed, are described in the following paragraphs.

4.4.1 Site Preparation Costs

It is assumed that preliminary site preparation will be performed by the responsible party (or site owner). The amount of preliminary site preparation will depend on the site. Site preparation responsibilities include site design and layout, surveys and site logistics, legal searches, access rights and roads, preparations for support and decontamination facilities, utility connections, and auxiliary buildings. Since these costs are site-specific, they are not included as part of the site preparation costs in this cost estimate.

Certain site preparation activities, such as excavating hazardous waste from the contaminated site, will be required at all sites and are therefore included in this estimate. Cost estimates for site preparation are based on rental costs for operated heavy equipment, labor charges, and equipment fuel costs.

An excavation rate of 9.1 tph is assumed for all cleanup scenarios using the 3.3 tph cyclone furnace. It is assumed the minimum rental equipment required to achieve an excavation rate of approximately 9.1 tph includes three excavators, one box dump truck, and one backhoe. The operation of this equipment will consume approximately 14 gallons of diesel fuel per hour. It is also assumed excavation activities will be conducted 12 hours a day, 5 days a week. An excavation rate of 45.5 tph is assumed for the cost estimate based on the use of a larger cyclone furnace (capable of treating 20 tph). It is further assumed that an excavation rate of 45.5 tph will require five times as much equipment, labor, and diesel fuel as an excavation rate of 9.1 tph. Excavation costs are itemized in Table 7.

Table 7. Excavation Costs

Item	Cost
Excavator	$1,260/week
Box dump truck	$525/week
Backhoe	$585/week
Supervisor	$40/hour
Excavator operator	$30/hour
Dump truck operator	$30/hour
Backhoe operator	$30/hour
Diesel fuel	$1/gallon

4.4.2 Permitting and Regulatory Costs

Permitting and regulatory costs are generally the obligation of the responsible party (or site owner), not of the vendor. These costs may include actual permit costs, system monitoring requirements, and/or the development of monitoring and analytical protocols. Permitting and regulatory costs can vary greatly because they are site- and waste-specific. No permitting or regulatory costs are included in this analysis. Depending on the treatment site however, this may be a significant factor since permitting activities can be both expensive and time consuming.

4.4.3 Equipment Costs

Major pieces of equipment include the:

- Cyclone furnace
- Heat exchanger
- Feed system
- Baghouse
- Quench tower
- Scrubber

The cyclone furnace cost supplied by B&W was used. It was comparable to an independent cost estimate. All other equipment costs were estimated from various references. The primary references used were the third edition of *Plant Design and Economics for Chemical Engineers* by M.S. Peters and K.D. Timmerhaus [1] and the fourth edition of the *Office of Air Quality Planning and Standards Cost Control Manual* [2]. Total equipment costs for the 3.3 tph cyclone furnace vitrification system are estimated to be approximately $3,500,000; equipment costs for the 20 tph system are estimated to be approximately $11,600,000. For each system, a useful life of 15 years and an interest rate of 10 percent are assumed.

It is assumed no rental equipment or purchased support equipment will be required for operation. Support equipment refers to pieces of purchased equipment necessary for operation but not integral to the system.

The commercial-scale cyclone furnace will be capable of treating 3.3 tph of contaminated soil and will require approximately 100 million Btu/hr. System accessories will include a feed system (holding tank, mixer, and feed nozzle) and an air pollution control system. The effluent flue gas flows through an air-to-air heat exchanger where it is cooled from 2000°F to 1300°F while heating the influent combustion air from ambient temperature to 800°F. Following the heat exchanger, the flue gas is cooled to 200°F in a water quench tower. The cooled gas flows to a lime spray dryer for acid gas removal and then to a pulse-jet baghouse for particulate removal.

The total equipment cost is calculated and is annualized using the following formula:

$$A = \frac{C * i * (1 + i)^n}{(1 + i)^n - 1}$$

where: A = annualized cost, \$
C = capitalized cost, \$
i = interest rate, %
n = useful life, years

The annualized cost (rather than depreciation) is used to calculate equipment costs incurred by a site. The annualized equipment cost is prorated to the actual time the reactor is commissioned to treat a hazardous waste (including assembly, shakedown and testing, treatment, and disassembly). The prorated cost is then normalized relative to tons of soil treated.

4.4.4 Startup and Fixed Costs

Mobilization includes both transportation and assembly. The cyclone furnace vitrification system will be difficult to transport and its relocation will require a great deal of time and planning. For the purpose of this estimate, transportation costs are included with mobilization rather than demobilization. Transportation activities include moving the system and the workers to the site. As a rough estimate, it is assumed that ten tractor-trailers will be required to transport the commercial-scale cyclone furnace soil vitrification system. A 1,000 mile basis is assumed at a rate of \$1.65 per mile per legal load (including drivers). Transportation costs for the 30 workers are based on a \$300 one-way airfare per person. The accuracy of this airfare estimate was confirmed by an examination of one-way airfares for flights from Akron, Ohio (near Alliance) to Dallas-Fort Worth and to Fort Lauderdale, both of which are approximately 1000 miles from Akron.

Assembly consists of unloading the system from the trucks and trailers and reassembling the furnace. It is assumed that unloading the equipment will require the use of an operated 50-ton crane for 6 weeks at a cost of \$6,360 per week. Assembly is assumed to require 30 people working 12 hours per day, 5 days per week, for 6 weeks. Labor charges during assembly consist of wages (\$40 per hour) and living expenses (refer to subsection 4.4.5).

This cost estimate assumes that 6 weeks of shakedown and testing will be required after assembly and prior to the commencement of treatment. During this time, the system components are tested individually. It is estimated that 15 workers will be required for 12 hours per day, 5 days per week during shakedown and testing. Labor costs consist of wages (\$40 per hour) and living expenses (refer to subsection 4.4.5).

Working capital consists of the amount of money currently invested in supplies, energy, and spare parts kept on hand [1]. The working capital for this system is based on maintaining a 1-month inventory of these items. For the calculation of working capital, 1 month is defined as one-twelfth of a year, or approximately 21.7 working days.

Insurance is approximately 1 percent of the total equipment capital costs, while taxes are 2 to 4 percent. The cost of insurance for a hazardous waste process can be several times more than this. Insurance and taxes together are assumed, for the purposes of this estimate, to be 10 percent of the equipment capital costs [1]. These costs have been prorated to the actual time the cyclone furnace is commissioned to treat contaminated waste on a site (including assembly, shakedown and testing, treatment, and disassembly).

The cost for the initiation of monitoring programs has not been included in this estimate. Depending on the site, local authorities may impose specific guidelines for monitoring programs. The stringency and frequency of monitoring required may have a significant impact on the project costs.

An annual contingency cost of 10 percent of the annualized equipment capital costs is allowed to cover additional costs caused by unforeseen or unpredictable events, such as strikes, storms, floods, and price variations [1]. The annual contingency cost has been prorated to the actual time the reactor is commissioned to treat hazardous waste (including assembly, shakedown and testing, treatment, and disassembly).

4.4.5 Labor Costs

Labor costs consist of wages and living expenses. Personnel requirements per shift during treatment are estimated at: four feed operators at \$25 per hour, two maintenance operators at \$30 per hour, and four system operators at \$40 per hour. Rates include overhead and administrative costs. It is assumed that personnel will work an average of 40 hours per week at three shifts for a 24-hour, 5-day-per-week operation.

Living expenses depend on several factors: the duration of the project, the number of local workers hired, and the geographical location of the project. Living expenses for all personnel who are not local hires consist of per diem and rental cars, both charged at 7 days per week for the duration of the treatment. Per diem varies by location, but for the purposes of this report is assumed to be \$60 per day per person. Six rental cars are required for a 24-hour operation and are available for \$30 per day per car. Depending on the length of the project, B&W may elect to hire local personnel and train them in the operation of the furnace, thus eliminating living expenses.

4.4.6 Supplies Costs

For this estimate, supplies consists of chemicals and spare parts. Lime requirements for scrubber operation are estimated to cost approximately $28,500 per year of operation (a year of operation is defined as a year of time spent actually processing waste). Spare parts consist of baghouse bags, which cost approximately $12,800 per set and are assumed to require annual replacement during periods of treatment.

4.4.7 Consumables Costs

The cyclone furnace consumes natural gas at a rate of approximately 100 million Btu/hr. The cost of natural gas is estimated as $5.10 per million Btu with no monthly fee, yielding a fuel cost of approximately $510 per hour of operation.

The projected air usage for the baghouse is approximately 85 scfm of 60 to 100 psig air; air costs are estimated at $0.20 per 1000 standard cubic feet (scf).

The electricity requirement for the baghouse fans is approximately 414,600 kilowatt-hours (kWh) per year of operation. It is estimated that the electrical requirements for the scrubber will have an associated cost of approximately $5 per hour of operation. The cost estimate assumes that electricity can be obtained for a flat rate of $0.06 per kWh with no monthly charge.

The quench tower requires 34 gpm of water. Smaller quantities of water are used in the scrubber and in miscellaneous other applications yielding an estimated total water usage rate of 40 gpm. Water costs are estimated at $1.10 per 1000 gallons.

4.4.8 Effluent Treatment and Disposal Costs

B&W is currently investigating the feasibility of mixing the baghouse solids into the feed and recycling them through the system. If this process change is found to be feasible, it will be implemented in the commercial-scale system and it will not be necessary to dispose of the baghouse solids. The baghouse solids generated during the SITE demonstration were found to be hazardous and will therefore require disposal as a hazardous waste and/or additional treatment.

The water from the quench tower should be suitable for discharge to a municipal sewer system. The responsible party or site owner should obtain a discharge permit from the local municipality if possible. If no sewer service is available, the site owner or responsible party must obtain a direct discharge permit or arrange for disposal by other means. It should not be necessary to treat the water prior to discharge, but this must be determined on a site-specific basis.

Onsite treatment and disposal costs are restricted to onsite storage (if necessary) of the water from the quench tower and are assumed to be the obligation of the site owner or responsible party. Offsite treatment and disposal costs consist of wastewater disposal fees and are assumed to be the obligation of the responsible party (or site owner). These costs may significantly add to the total cleanup cost.

4.4.9 Residuals and Waste Shipping, Handling, and Transport Costs

It is assumed that the only residual generated by this process will be the slag. The slag generated during the SITE demonstration passed the TCLP test; as a result, it is anticipated that the slag will be disposed of in a sanitary landfill. The leachability of the slag from actual wastes must be determined on a site-specific basis. Potential waste disposal costs include storage, transportation, and treatment costs and are assumed to be the obligation of the responsible party (or site owner). These costs could significantly add to the total cleanup cost.

4.4.10 Analytical Costs

No analytical costs are included in this cost estimate. Standard operating procedures for B&W do not require sampling or analytical activities. The client may elect or may be required by local authorities to initiate a sampling and analytical program at their own expense. If specific sampling and monitoring criteria are imposed by local authorities, these analytical requirements could contribute significantly to the cost of the project.

4.4.11 Facility Modification, Repair, and Replacement Costs

Maintenance labor and material costs vary with the nature of the waste and the performance of the equipment. For estimating purposes, total annual maintenance costs (labor and materials) are assumed to be 10 percent of annualized equipment costs. Maintenance labor typically accounts for two thirds of the total maintenance costs and has previously been accounted for under in subsection 4.4.5. Maintenance material costs are estimated at one third of the total maintenance cost and are prorated to the entire period of treatment. Costs for design adjustments, facility modifications, and equipment replacements are included in the maintenance costs.

4.4.12 Site Demobilization Costs

Demobilization costs are limited to disassembly costs; transportation costs are accounted for under mobilization. Disassembly consists of taking the cyclone furnace apart and loading it onto ten trailers for transportation. It requires the use of an operated 50-ton crane, available at $6,360 per week, for 3 weeks. Additionally, disassembly requires a 30-person crew working 12-hour days, 5 days a week, for 3 weeks. Labor costs consist of wages ($40 per hour per person) and living expenses (refer to subsection 4.4.5).

Site cleanup and restoration are limited to the removal of all equipment from the site. These costs have been previously incorporated into the disassembly costs. Requirements regarding the filling, grading, or recompaction of the soil will vary depending on the future use of the site and are assumed to be the obligation of the responsible party (or site owner).

4.5 *Results of Economic Analysis*

The costs associated with the operation of the cyclone furnace, as presented in this economic analysis, are defined by 12 cost categories that reflect typical cleanup activities encountered on Superfund sites. Each of these cleanup activities is defined and discussed, forming the bases for the cost analysis presented in Table 8.

Table 8. Treatment Costs for 3.3 tph Cyclone Furnace Vitrification System Treating 20,000 Tons of Contaminated Soil

	Cost ($/ton)		
Item	60% online	70% online	80% online
Site Preparation	31.37	31.37	31.37
Permitting and Regulatory Costs	—	—	—
Equipment Cost Incurred	43.83	38.52	34.53
Startup and Fixed Costs	58.67	58.94	59.48
Labor	219.95	188.53	164.96
Supplies	2.02	1.87	1.76
Consumables	157.96	157.96	157.96
Effluent Treatment and Disposal	—	—	—
Residuals Handling and Transport	—	—	—
Analytical Costs	—	—	—
Facility Modification, Repair and Replacement	1.24	1.06	0.93
Site Demobilization	13.83	13.83	13.83
Total Operating Costs	528.88	492.09	464.84

The percentage of the total cost contributed by each of the 12 cost categories is shown in Table 9.

Table 9. Treatment Costs as Percentages of Total Costs for 3.3 tph Cyclone Furnace Treating 20,000 Tons of Contaminated Soil

	Cost (as % of total cost)		
Item	60% online	70% online	80% online
Site Preparation	5.9	6.4	6.7
Permitting and Regulatory Costs	—	—	—
Equipment Cost Incurred	8.3	7.8	7.4
Startup and Fixed Costs	11.1	12.0	12.8
Labor	41.6	38.3	35.5
Supplies	0.4	0.4	0.4
Consumables	29.9	32.1	34.0
Effluent Treatment and Disposal	—	—	—
Residuals Handling and Transport	—	—	—
Analytical Costs	—	—	—
Facility Modification, Repair and Replacement	0.2	0.2	0.2
Site Demobilization	2.6	2.8	3.0
Total Operating Costs	100.0	100.0	100.0

B&W states that coal-fired cyclone furnaces frequently operate with online factors of over 90 percent. The online factor for a cyclone furnace being used to vitrify soil is unknown, so online factors of 60 percent, 70 percent, and 80 percent were used to estimate the cost of cyclone furnace vitrification. The online factor is used to adjust the unit treatment cost to compensate for the fact that the system is not online constantly because of maintenance requirements, breakdowns, and unforeseeable delays. Through the use of the online factor, costs incurred while the system is not operating are incorporated into the unit cost.

The B&W cyclone furnace vitrification system is expected to be capable of a week of continuous operation; only one startup should be required each week unless problems arise. In fact, the system is believed to be capable of operating continuously (24 hours per day, 7 days per week) for extended periods of time and B&W will most likely choose to conduct site remediations in this manner. If B&W chooses to operate continuously, adjustments must be made to the cost estimates for fuel, labor, and all other items which are affected by the length of time that the system is onsite.

The feed rate during the SITE Demonstration Test was approximately 170 lb/hr and the furnace consumed approximately 5 million Btu/hr. The results of this pilot-scale demonstration were used to estimate the results of commercial-scale operation. The "six-tenths" rule was used to estimate the cost of equipment for the commercial-scale system from available cost data for equipment of a different capacity [1]. The Marshall & Swift cost index was used to estimate current costs (fourth quarter of 1991) from earlier cost data [1]. It is assumed the commercial-scale unit will have a feed rate of 3.3 tph and will require approximately 100 million Btu/hr. For this feed rate, the results of the analysis show a unit cost ranging from $465 per ton to $529 per ton for 80 and 60 percent online conditions, respectively.

These costs are considered order-of-magnitude estimates as defined by the American Association of Cost Engineers. The actual cost is expected to fall between 70 percent and 150 percent of these estimates. Since costs were estimated from a pilot unit, the range may actually be wider.

Table 10 compares estimated unit treatment costs for sites containing 10,000, 20,000, and 100,000 tons of contaminated soil, while Table 11 shows the percentage of the treatment costs contributed by each of the 12 cost categories. All variables except total amount of contaminated soil are held constant. In particular, all three estimates utilize a 3.3 tph cyclone furnace and a 60 percent online factor. If the 3.3 tph cyclone furnace is used to remediate a site containing less than 20,000 tons of contaminated soil (all other variables remaining constant), the startup and fixed costs will become more of a factor. Unit costs derived from startup and from fixed expenses will be higher, but unit costs derived from operating expenses will remain approximately the same. Variations in the impacts of the 12 cost categories can be seen in Tables 10 and 11.

For example, if this system is applied to a site containing 10,000 tons of contaminated soil, the unit treatment costs (using a 60 percent online factor) are estimated at $601 per ton of soil. If the 3.3 tph cyclone furnace is used at a site containing over 20,000 tons of contaminated soil (all other variables remaining constant), the startup and fixed costs will become less of a factor. Unit costs derived from startup and from fixed expenses will be lower, but unit costs derived from operating expenses will remain approximately the same. For example, if this system is applied to the remediation of a site containing 100,000 tons of contaminated soil, the unit treatment costs (using a 60 percent online factor) are estimated at $472 per ton of soil.

Table 10. Treatment Costs for 3.3 tph Cyclone Furnace Vitrification System Operating with a 60% Online Factor

Item	Cost ($/ton) 10,000 tons	20,000 tons	100,000 tons
Site Preparation	31.37	31.37	31.37
Permitting and Regulatory Costs	---	---	---
Equipment Cost Incurred	50.46	43.83	38.53
Startup and Fixed Costs	109.90	58.67	17.69
Labor	219.95	219.95	219.95
Supplies	2.02	2.02	2.02
Consumables	157.96	157.96	157.96
Effluent Treatment and Disposal	---	---	---
Residuals Shipping, Handling and Transport	---	---	---
Analytical Costs	---	---	---
Facility Modification, Repair and Replacement	1.24	1.24	1.24
Site Demobilization	27.67	13.83	2.77
Total Operating Costs	600.57	528.88	471.53

It will take over 8 years to remediate a site containing 100,000 tons of contaminated soil with the 3.3 tph system. For this volume of soil, a larger unit would be more appropriate. Although B&W does not currently have any plans to construct a larger system, a preliminary cost estimate was prepared for a system capable of treating 20 tph of contaminated soil.

Table 12 compares estimated unit treatment costs for the use of 3.3 tph and 20 tph systems at a site containing 100,000 tons of contaminated soil, while Table 13 shows the percentage of the treatment costs contributed by each of the 12 cost categories. All variables except feed rate are held constant. In particular, both estimates utilize a 60 percent online factor. This preliminary analysis indicates that it will cost $505 per ton to remediate a site containing 100,000 tons of contaminated soil using the 20 tph system (assuming a 60 percent online factor). When the larger system is used, the treatment time is approximately 1.3 years and the equipment is onsite for approximately 1.6 years. Transportation and onsite assembly of the larger unit, however, could present difficulties.

Table 11. Treatment Costs as % of Total Costs for 3.3 tph Cyclone Furnace Vitrification System Operating with a 60% Online factor

Item	Cost (as % of total cost) 10,000 tons	20,000 tons	100,000 tons
Site Preparation	5.2	5.9	6.7
Permitting and Regulatory Costs	---	---	---
Equipment Cost Incurred	8.4	8.3	8.2
Startup and Fixed Costs	18.3	11.1	3.8
Labor	36.6	41.6	46.6
Supplies	0.3	0.4	0.4
Consumables	26.3	29.9	33.5
Effluent Treatment and Disposal	---	---	---
Residuals Handling and Transport	---	---	---
Analytical Costs	---	---	---
Facility Modification, Repair and Replacement	0.2	0.2	0.3
Site Demobilization	4.6	2.6	0.6
Total Operating Costs	100.0	100.0	100.0

The costs excluded from this cost analysis are described in subsections 4.3 and 4.4. This analysis does not include values for 4 of the 12 cost categories, so the actual cleanup costs incurred by the site owner or responsible party may be significantly higher than the costs shown in this analysis.

4.6 *References*

1. Peters, M.S. and Timmerhaus, K.D. Plant Design and Economics for Chemical Engineers; Third Edition; McGraw-Hill, Inc: New York, 1980.

2. U.S. Environmental Protection Agency Office of Air Quality Planning and Standards. Cost Control Manual. PB90-169954. January, 1990.

Table 12. Treatment Costs for the Remediation of 100,000 Tons of Contaminated Soil Using Cyclone Furnace Vitrification System Operating with a 60% Online Factor

Item	Cost ($/ton) 3.3 tph System	20 tph System
Site Preparation	31.37	31.37
Permitting and Regulatory Costs	---	---
Equipment Cost Incurred	38.53	24.62
Startup and Fixed Costs	17.69	46.06
Labor	219.95	90.73
Supplies	2.02	2.02
Consumables	157.96	303.19
Effluent Treatment and Disposal	---	---
Residuals Shipping, Handling and Transport	---	---
Analytical Costs	---	---
Facility Modification, Repair and Replacement	1.24	0.68
Site Demobilization	2.77	6.57
Total Operating Costs	471.53	505.24

Table 13. Treatment Costs as Percentages of Total Costs for Cyclone Furnaces Treating 100,000 Tons of Contaminated Soil

Item	Cost (as % of total cost) 3.3 tph system	20 tph system
Site Preparation	6.7	6.2
Permitting and Regulatory Costs	---	---
Equipment Cost Incurred	8.2	4.9
Startup and Fixed Costs	3.8	9.1
Labor	46.6	18.0
Supplies	0.4	0.4
Consumables	33.5	60.0
Effluent Treatment and Disposal	---	---
Residuals Handling and Transport	---	---
Analytical Costs	---	---
Facility Modification, Repair and Replacement	0.3	0.1
Site Demobilization	0.6	1.3
Total Operating Costs	100.0	100.0

Appendix A
Process Description

A.1 *Introduction*

The B&W cyclone furnace technology is a well-established design for coal combustion. Previous applications of this technology to municipal solid waste (MSW) ash containing heavy metals led to its use on metals-contaminated soils that also contain organic constituents. B&W's cyclone furnace is an innovative thermal technology which may offer advantages in treating soils containing organics, heavy metals, and/or radionuclide contaminants. The pilot scale unit used during the SITE demonstration simulates typical full-scale commercial cyclone boilers being used for steam generation in power plants.

The demonstration was conducted to evaluate the ability of the B&W cyclone furnace to vitrify contaminated soil and waste (liquids and solids). The process was demonstrated using an SSM provided by the EPA's Risk Reduction Engineering Laboratory in Edison, New Jersey. SSMs are well-characterized, clean soils which are spiked with known concentrations of specified contaminants.

A.2 *The Cyclone Furnace*

The pilot unit, shown in Figure A-1, is a scaled-down version of a B&W commercial coal combustion cyclone furnace. The furnace is watercooled and similar to B&W's single cyclone, front-wall fired cyclone burners. It has a 6-million Btu/hr heat input.

For the demonstration, natural gas was introduced into the cyclone furnace. Preheated combustion air (nominal 800°F) entered tangentially into the cyclone.

The feed SSM was introduced via a soil disperser (atomizer) at the center of the cyclone. The gas exiting the cyclone barrel had a temperature of approximately 3000°F while the gas exiting the upper furnace had a temperature over 2000°F with a 2-second residence time.

The energy requirements for vitrification of the SSM were 15,000 Btu/lb. Given the much larger surface area-to-volume ratio of the pilot unit, one may expect a full-scale unit to achieve lower energy requirements.

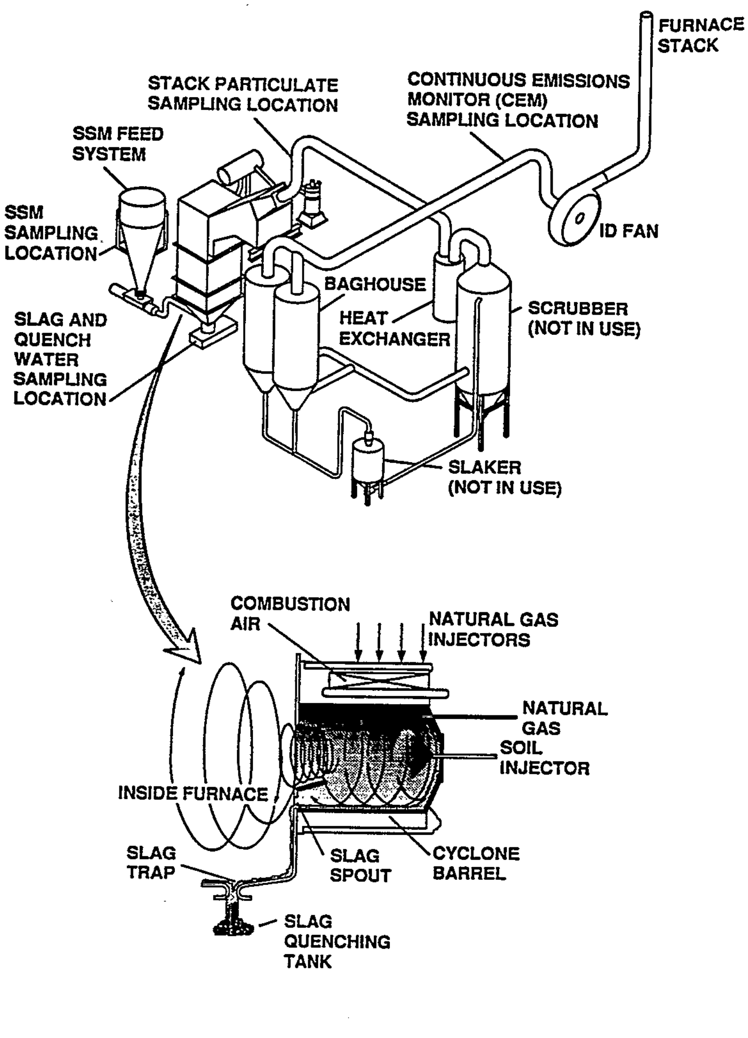

Figure A-1. Cyclone Test Facility.

The cyclone is designed to achieve very high heat release rates, temperatures, and turbulence. Particulate matter from the soil stream is retained along the walls of the furnace by the swirling action of the combustion air and is incorporated into the molten slag layer. Organic material in the soil is vaporized or combusted in the molten slag. The slag, which has a temperature of 2400°F, exits the cyclone furnace from a tap at the cyclone throat and drops into a water-filled tank where the material is quenched. A small portion of the soil exits as flyash in the flue gas and is collected in a baghouse. A heat exchanger cools stack gases to approximately 200°F before they enter the baghouse. The cyclone facility is also equipped with a scrubber to control any acid gases that may be generated. For this demonstration, the scrubber was not required since chlorinated compounds were not spiked into the SSM.

The SSM was delivered onsite in 55-gallon drums and fed to the system by connecting the SSM transport drum to the feed cone. A system of dust-free valves was opened to allow a screw feeder to transfer the soil to the cyclone feed hopper. A screen above the feed hopper removed oversized materials and a mixer kept the SSM from settling in the feed hopper. After passing the screw feeder, the soil was fed to the furnace pneumatically, utilizing a small fraction of the combustion air.

A variety of sampling ports and instrument monitors were fitted to the pilot unit. A system of stairways and walkways provided access to all required gas stream sampling points.

Appendix B

Vendor's Claims

B.1 Site Demonstration Vendor's Claims

The effectiveness of the B&W Cyclone Furnace Vitrification Technology at destroying organics and immobilizing heavy metals and simulated radionuclides in a non-leachable slag was evaluated during the SITE Demonstration. To perform this evaluation, the following critical and non-critical Vendor's Claims were developed by Babcock & Wilcox, based on discussions with the U.S. EPA, for evaluation in the Demonstration. These claims are presented in Table B-1.

B.2 Comparison of Performance Results from the Two SITE Emerging Technologies Projects with the Vendors Claims

B.2.1 Synthetic Soil Matrix and Feed Conditions

Two Superfund Innovative Technology Evaluation (SITE) Emerging Technology projects were conducted prior to the SITE Demonstration. These two projects, Phase I and Phase II, were conducted to establish the feasibility of the cyclone vitrification process for dry soil (Phase I) and wet soil (Phase II) treatment. In each project, measurements were made to evaluate TCLP leachabilities, volume reduction, and materials and heavy metals mass balances.

A synthetic soil matrix formulated by EPA was used for all cyclone testing. Both clean and spiked SSM were obtained from the EPA Risk Reduction Engineering Laboratory (RREL) Releases Control Branch in Edison, NJ. SSM, used by EPA for treatment technology evaluations, has been well-characterized in previous studies [1]. Clean soil was used for furnace conditions optimization. The spiked SSM used in the Emerging Technologies projects contained 7,000 ppm (0.7 percent) lead, 1,000 ppm (0.1 percent) cadmium, and 1,500 ppm (0.15 percent) chromium.

Table B-1. B&W Claims for Cyclone Vitrification Technology

Parameter	Claim
<u>Critical</u>	
TCLP	Produce a vitrified slag that does not exceed Toxicity Characteristic Leaching Procedure (TCLP) regulatory levels for cadmium (i.e., <1 mg/L), lead (<5 mg/L), and chromium (<5 mg/L).
Slag to Flyash Ratio	Achieve at least a 10 to 1 ratio (dry weight basis) of slag to flyash.
Non-Volatile Metals Capture (Cr) in the Slag	Capture at least 60% (by weight) of the non-volatile metal chromium from the dry, untreated SSM in the vitrified slag.
Volume Reduction	Achieve at least a 25 percent volume reduction in solids when comparing product solid to untreated SSM.
DREs	Achieve a 99.99% destruction and removal efficiencies DREs for each organic contaminant spike (anthracene and dimethylphthalate).
CO, THC, Particulates	Comply with emission limits for CO, total hydrocarbons (THC), and particulates from the stack as stipulated by 40 CFR 264 (i.e., CO of <100 ppm, THC of <20 ppm, and particulates of <0.08 gr/dscf at 7% oxygen).
<u>Non-Critical</u>	
ANS 16.1 Simulated Radionuclide Leachability	Produce a slag that immobilizes (passes leaching standards) radionuclides as measured by the American Nuclear Society test (ANS) 16.1 (i.e., ANS 16.1 calculated leachability index (LI) >6).
Non-Volatile Radionuclide Capture in the Slag	Capture at least 60% (by weight) of the non-volatile metals strontium and zirconium in the vitrified slag.

In Phase I, dry SSM was processed at feed rates of 50 to 150 lb/hr. In Phase II, wet SSM was processed at feed rates of 100 to 300 lb/hr (dry basis).

Approximately 11 tons of spiked and unspiked SSM were processed during each of the two project Phases.

B.2.2 Performance Results

A comparison of Phase I and II results against the Vendor's Claims developed for the Demonstration is presented in Table B-2. Not all of the Demonstration claims were tested during these projects (e.g., DRE, ANS 16.1 were omitted). All claims tested were met or exceeded during these Emerging Technology projects (the Claims were finalized on the basis of these results).

Table B-2. Phase I & Phase II Performance vs. Vendor Claims

Parameter	Performance Criterion in Vendor's Claim	Performance Measured in Phase I[a]	Performance Measured in Phase II[a]
TCLP-Cadmium	≤ 1.0 mg/L	0.13 mg/L	0.07 mg/L
TCLP-Lead	≤ 5.0 mg/L	0.20 mg/L	0.20 mg/L
TCLP-Chromium	≤ 5.0 mg/L	0.11 mg/L	0.04 mg/L
Slag to Flyash Ratio	≥ 10:1	14.6:1	34:1
Non-Volatile Metal (Cr) Capture in the Slag	≥ 60%	80-95%	78-95%
Volume Reduction	≥ 25%	35%	25%

a Average results where several measurements were made.

B.3 Comparison of Performance Results from the SITE Demonstration with the Vendors Claims

B.3.1 Synthetic Soil Matrix and Feed Conditions

On the basis of the Phase I and II Emerging Technology projects, Babcock & Wilcox was asked to perform a SITE Demonstration. For the Demonstration, a wet SSM was used. Demonstration goals included the vendor's claims given above.

The SSM used in the SITE Demonstration contained 7,000 ppm lead, 1,000 ppm cadmium, and 4,500 ppm chromium; 6,500 ppm anthracene; 8,000 ppm dimethylphthalate; and the three simulated radionuclides: 4,500 ppm bismuth, 4,500 ppm strontium, and 4,500 ppm zirconium. The rationale for B&W's choice of radionuclide surrogates is as follows: Bismuth was used as a surrogate for volatile radionuclides important at DOE/DOD sites such as cesium (cold cesium was originally proposed but found to be excessively expensive). Cold strontium was used as a surrogate for radioactive strontium (the cold version of the radionuclide is the best possible surrogate). Zirconium was considered an excellent surrogate for radioactive thorium and uranium from the standpoint of both volatility and chemical behavior (all are oxophillic and tend to be in the +4 oxidation state).

A total of 3 tons of SSM were processed during the Demonstration at a feed rate of 170 lb/hr.

B.3.2 Performance Results

A comparison of the Demonstration results against the Vendor's Claims developed for the Demonstration is presented in Table B-3. All claims tested were exceeded during the Demonstration.

Table B-3. SITE Demonstration Performance vs. Vendor Claims

Parameter	Performance Criterion in Vendor's Claim	Performance Measured in Demonstration[a]
TCLP-Cadmium	≤ 1.0 mg/L	0.12 mg/L
TCLP-Lead	≤ 5.0 mg/L	0.29 mg/L
TCLP-Chromium	≤ 5.0 mg/L	0.30 mg/L
Slag to Flyash Ratio	≥ 10:1	15.6:1
Non-Volatile Metal (Cr) Capture in the Slag	≥ 60%	76%
Non-Volatile Metal (Sr) Capture in the Slag[b]	≥ 60%	88%
Non-Volatile Metal (Zr) Capture in the Slag[b]	≥ 60%	96%
Volume Reduction	≥ 25%	28.1%
DRE-Anthracene	≥ 99.99%	>99.996%
DRE-Dimethylphthalate	≥ 99.99%	>99.998%
CO	<100 ppm	4.8-54.1 ppm
THC	<20 ppm	<5.9-18.2 ppm
Particulates	≤ 0.08 gr/dscf[c]	0.001 gr/dscf[c]
ANS 16.1 Leachability-Bismuth[b]	LI > 6	LI = 13.4
ANS 16.1 Leachability-Strontium[b]	LI > 6	LI = 13.1
ANS 16.1 Leachability-Zirconium[b]	LI > 6	LI = 8.7

a Average results where several measurements were made.
b Non-critical parameter.
c Corrected to 7 percent oxygen.

B.4 Summary

The Babcock & Wilcox 6-million Btu/hr pilot cyclone furnace met or exceeded all critical and non-critical Vendor's Claims. Because these performance results were measured on a pilot cyclone furnace configured as a utility boiler, and by no means optimized for soil vitrification, a unit designed for dedicated soil vitrification may improve process performance and throughput.

B.5 Reference

1. P. Esposito, J. Hessling, B. Locke, M. Taylor, M. Szabo, R. Thurnau, C. Rogers, R. Traver, and E. Barth, "Results of Treatment Evaluations of a Contaminated Synthetic Soil," JAPCA, 39: 294 (1989).

Appendix C

SITE Demonstration Results

C.1 Introduction

This appendix summarizes the results of the SITE Demonstration Test of the B&W Cyclone Furnace Vitrification Technology. These results are also discussed in Section 3 of this report. A more detailed account of the demonstration may be found in the TER.

During the demonstration, the effectiveness of the process was evaluated by conducting three identical runs using a B&W pilot-scale unit (Runs 1, 2, and 3). In addition, a background run was conducted to determine baseline conditions (Run 0). Sampling of the feed SSM and waste streams was performed in accordance with the procedures outlined in the Demonstration Plan.

The emphasis of a SITE demonstration is for the technology to meet ARARs. The ability of the cyclone furnace to destroy semivolatile organics and immobilize heavy metals and simulated radionuclides into a non-leachable slag was evaluated. Results from this demonstration include TCLPs of the slag, metals partitioning, DREs, and emissions from the technology. The concentration of contaminants in the quench water and baghouse solids, as well as the slag-to-flyash ratio, volume reduction, radionuclide leachability from the slag, and SSM characteristics are also addressed.

Data regarding simulated radionuclides are suspect because the method has not been validated for these metals. Since the method's accuracy and precision are not well quantified, the data are used for information purposes only.

C.2 Slag Characteristics

During the demonstration, 94 percent of the non-combustible portion of the feed was transformed from loosely packed soil to a brittle, glass-like slag. The remaining 6 percent of the non-combustible feed was released in the flue gas as particulate matter. By comparing the particulate emission rate from the furnace outlet with the amount of slag produced per hour by the cyclone furnace, a relative measure of slag and flyash production can be calculated. This "slag-to-flyash ratio" is a comparative measure of solids generation and is calculated by dividing the mass of the slag (dry weight) by the mass of the flyash (dry weight). Average slag-to-flyash ratios of 14.5, 13.7, and 12.9 were obtained for Runs 1, 2, and 3, respectively. These results are consistent with Demonstration Test objectives and support B&W's claim that a greater than 10:1 ratio of slag-to-flyash ratio can be achieved using the cyclone furnace.

C.2.1 Leachability

TCLPs were performed on both the feed SSM and vitrified slag. The leachabilities obtained for these materials are summarized in Table C-1. Significant reductions were experienced for all the metals, particularly cadmium and lead, which were brought into compliance with regulatory limits as a result of cyclone vitrification treatment. The data demonstrate the cyclone furnace can immobilize cadmium, chromium, and lead so that regulatory compliance is achieved.

To verify that decreases in leachability are due to changes in the leaching behavior of the soil, and not due to lower concentrations of metals in the slag, the percent leachability of metals in the SSM and slag was determined by dividing the amount of each heavy metal which leached during the TCLP test from the SSM and slag by the total amount of each heavy metal which could be leached. These percent leachable metals are listed in Table C-2 and are based on average results for the demonstration. The results indicate the vitrification process decreases the leachability in the slag by changing the physical/chemical behavior of the soil.

ANS Method 16.1 (American National Standard Measurement of the Leachability of Solidified Low-Level Radioactive Wastes by a Short-Term Test Procedure) was

Table C-1. **Average TCLP Results from B&W SITE Demonstration Runs[a] (mg/L)**

	Cadmium	Chromium	Lead
SSM			
Run 1	52.0	2.29	90.8
Run 2	63.6	1.77	75.6
Run 3	34.2	3.87	125
Slag			
Run 1	<0.11[b]	0.15	<0.25
Run 2	0.19	0.37	<0.39[b]
Run 3	0.07	0.15	<0.29[b]

a Average values were calculated from nine individual samples collected over course of each run.

b If result was undetected, the detection limit was used in calculations for averages. This represents worst case scenario.

Table C-2. **Percentage of Leachable Metals from B&W Cyclone Furnace**

Heavy Metals	Total Metal in 100g sample (mg)	Metal Leached from 100g sample in TCLP Test (mg)	% of Metal Present That Leached
SSM			
Cadmium	126	99.8	79
Chromium	435	5.28	1.2
Lead	641	195	30
Slag			
Cadmium	10.6	0.24	2.3
Chromium	161	0.44	0.27
Lead	176	0.62	0.35

used to determine the leachability of the simulated radionuclides strontium, zirconium, and bismuth from the slag generated during the SITE demonstration. The method was modified to account for the irregular shape of the slag.

Although all other equations and data reduction procedures remain the same, the method accuracy and precision are not well quantified because the method has not been verified for the slag and the data are therefore suspect. Results from the ANS method are reported as a leachability index and presented in Table C-3.

C.2.2 Volume Reduction

Combustion of any carbonates, sulfates, and organics present in the SSM contributed to the volume reduction experienced during the Demonstration Test. The percent

Table C-3. **Leachability Index of Simulated Radionuclides**

Slag	Bismuth	Strontium	Zirconium
Run 1 Range	12.9-13.7	12.1-13.6	8.2-8.8
Mean	13.2	12.9	8.6
Run 2 Range	13.5-14.2	12.8-13.7	8.2-9.4
Mean	13.8	13.3	8.7
Run 3 Range	12.3-14.0	11.6-14.0	8.3-9.0
Mean	13.3	13.0	8.7

volume reduction of dry SSM after treatment (as determined by the volume of slag produced) was computed according to the following equation:

$$\text{Percent Volume Reduction} = \frac{V_f - V_s}{V_f} \times 100\%$$

Where:

V_f = Volume of the SSM feed on a dry weight basis

= Mass of the feed (dry basis) used for the run divided by the bulk density of the feed

V_s = Volume of the slag on a dry weight basis

= Mass of the slag produced for the run divided by the bulk density of the slag

The bulk density of the slag was initially analyzed using the American Society for Testing and Materials (ASTM) method for specific gravity (ASTM D854 Test Method for Specific Gravity of Soil). This method defines the specific gravity as the ratio of the mass of a unit volume of soil to the mass of the same volume of water. The result from this analysis could not be effectively employed in calculations using the bulk density values obtained for the feed.

The feed was re-analyzed using a method B&W developed for determining bulk density. This method determines bulk density by weighing the soil in a box of known volume. Bulk density is calculated as follows:

$$\text{Bulk density in lb/ft}^3 = \frac{W_1 - W_0}{V}$$

Where:

V = Volume of the box in ft^3

W_1 = Weight of the box with sample in pounds

W_0 = Original weight of the box in pounds

This method was also used to determine bulk density of the slag. Although the accuracy of the data obtained using this non-standardized method is questionable, comparisons between the SSM and slag data provide reliable results.

Table C-4 lists the percent volume reductions achieved using the slag bulk density values from the ASTM and B&W methods. The negative values for volume reduction calculated using the ASTM generated values for the slag specific density are inconsistent with both testing expectations and field observations. The results obtained using the B&W data, however, agreed with field observations and Demonstration Test objectives. These results confirm B&W's claim that an average of 25 percent reduction in the volume is experienced during treatment.

Table C-4. **Volume Reduction (%)**

Method of Bulk Density	Run 1	Run 2	Run 3	Avg
ASTM	-43.8	-32.7	-49.7	-42.0
B&W	31.2	32.0	23.5	28.9

C.3 Metals Partitioning

The fate of a metal spiked within the SSM was dependent on the relative volatility of the metal. The majority of the metals spiked within the SSM were either captured within the slag or the flyash; however, a small portion did escape to the ambient air. Metal emission data are presented in Table C-5.

Table C-5. **Summary of Metals Emissions**

		Emission rate (lb/h)		
Run No.	Location	Cd	Cr	Pb
1	Furnace Outlet	7.4×10^{-2}	4.3×10^{-2}	3.6×10^{-1}
	Stack	3.8×10^{-5}	5.8×10^{-5}	1.2×10^{-4}
2	Furnace Outlet	7.9×10^{-2}	4.4×10^{-2}	4.2×10^{-1}
	Stack	1.5×10^{-4}	1.9×10^{-4}	7.1×10^{-4}
3	Furnace Outlet	7.8×10^{-2}	6.4×10^{-2}	4.7×10^{-1}
	Stack	9.4×10^{-6}	2.1×10^{-5}	4.8×10^{-5}

Percent retentions in the slag of the metals initially present within the SSM were evaluated by comparing the total mass of metals in the SSM to the total mass of metals in the slag.

These values were determined using the following equation:

$$\text{Percent Metal Retention} = \frac{MSi}{MPi + MSi} \times 100\%$$

Where:

pP = Percentage of non-combustible SSM that becomes furnace outlet particulate

= Furnace outlet particulate emission rate divided by the non-combustible portion of the feed

pS = Percentage of non-combustible SSM that becomes slag

= 100% - pP

MPi = Percentage of metal of interest in the furnace outlet particulate

= pP x concentration of metal of interest in furnace outlet particulate

MSi = Percentage of metal of interest in the slag material

= pS x concentration of metal of interest in slag

MPi + MSi = Percentage of metal of interest in SSM

Table 5 in Section 3 lists the percent metal retention of the six metals spiked in the SSM. On the average, over 75 percent of the chromium was incorporated in the vitrified slag. This supports B&W's claim that greater than 60 percent of the chromium (by weight) would be trapped within the vitrified slag. Approximately 88 and 97 percent of the strontium and zirconium, respectively, were captured within the slag. These results are consistent with the non-volatile nature of these metals. The more volatile bismuth, cadmium, and lead experienced lower captures. The bulk of these metals partitioned to the flue gas and were eventually captured by the baghouse.

Comparisons between the emissions entering the baghouse from the furnace outlet and exiting the stack yield an average particulate removal efficiency of 99.89 percent. The majority of the metals exiting the furnace in the flue gas are captured within the baghouse, although small amounts were detected in the stack gas.

C.4 *Air Emissions*

C.4.1 Particulate

Particulate emissions were measured at the furnace outlet prior to the air pollution control devices and at the stack for all runs. Particulate emissions out of the stack averaged 0.0008 gr/dscf (corrected by 7 percent O_2), or 0.01 lb/hr, which is well under the RCRA regulatory limit of 0.08 gr/dscf. Average particulate emissions from the furnace outlet were 0.806 gr/dscf (corrected to 7 percent O_2), or 6.07 lb/hr. Before furnace outlet emissions reached the stack, they were controlled by a baghouse, which had an average removal efficiency of 99.89 percent efficiency. Table 6 in Section 3 summarizes particulate testing during the demonstration.

C.4.2 DRE

In addition to producing a slag capable of retaining a high percentage of the heavy metals, the cyclone furnace achieved the organic destruction efficiency required of RCRA hazardous waste incinerators (99.99 percent). By comparing the concentrations of the spiked organic contaminants, anthracene and dimethylphthalate, present in the SSM to their concentrations in the stack gas, DREs for these compounds were calculated as follows:

$$DRE\ (\%) = \frac{W_{in} - W_{out}}{W_{in}} \times 100\%$$

Where:

W_{in} = Mass feed rate of the POHC of interest in the waste stream feed to the furnace

W_{out} = Mass emission rate of the same POHC present in exhaust emissions prior to release to the atmosphere

As listed in Table C-6, the cyclone furnace was capable of removing greater than 99.99 percent of both anthracene and dimethylphthalate. Because these organics are relatively difficult to destroy, it is projected that the commercial-scale cyclone furnace will be capable of achieving DREs of at least 99.99 percent for all or nearly all organics.

Table C-6. DREs (%)

Compound	Run 1	Run 2	Run 3	Average
Anthracene	>99.996	>99.997	>99.996	>99.997
Dimethyl phthalate	>99.998	>99.998	>99.998	>99.998

C.4.3 PICs

VOC concentrations were measured by the Volatile Organic Sampling Train (VOST) analysis. Average VOC concentrations are presented in Table C-7. Run 0 data

Table C-7. Summary of Volatile Organic Concentrations in Stack Gas from B&W SITE Demonstration ($\mu g/m^3$)[a]

Compound	Trip Blank[b]	Run 0	Run 1	Field Blank (Run 1)	Run 2	Run 3
Chloromethane	c	c	c	c	<0.50-1.51[e]	<0.50-1.85[a,g]
Chloroethane	c	c	c	c	<0.50-0.96[e]	c
Methylene chloride	0.40	<0.25-1.15[f]	2.95-3.69	2.20	0.81-5.26	1.01-20.8
Acetone	c	<0.50-2.50[f]	<0.50-5.89[e]	c	c	<0.50-41.1[f]
Carbon Disulfide	1.45	d	<0.25-10.2[f]	2.20	<0.25-1.28[e]	<0.25-1.61[f]
Chloroform	d	0.48-0.70	<0.25-0.45[e]	d	<0.25-0.37[f]	<0.25-0.42[e]
1,1,1-Trichloroethane	d	0.48-0.73	29.8-31.4	d	14.4-18.7	<0.25-20.2[f]
Carbon tetrachloride	d	d	<0.25-3.81[e]	d	<0.25-1.60[e]	<0.25-2.52[e]
Trichloroethene	d	d	d	d	0.25-0.27	d
Benzene	d	1.06-3.47	2.02-2.78	d	1.26-2.34	1.44-7.29
Tetrachloroethene	d	1.41-2.23	1.01-1.12	d	0.84-1.01	<0.25-0.94[f]
Toluene	d	1.22-8.32	1.79-4.85	0.25	1.32-1.76	0.72-2.71
Ethylbenzene	d	0.67-5.54	<0.25-0.91[f]	d	<0.25-0.26[e]	0.25-0.51
Total xylenes[h]	0.85	3.04-20.4	0.63-1.92	0.70	0.64-1.26	1.41-2.06

a No field blank was taken for Run 0. No compounds were detected in the lab blanks and field blanks for Run 2/3.
b Concentrations are based on a sample volume of 20L.
c Not detected. Detection limit 0.50 $\mu g/m^3$.
d Not detected. Detection limit 0.25 $\mu g/m^3$.
e Emissions were detected in 1 out of 3 samples.
f Emissions were detected in 2 out of 3 samples.
g An estimated 15 mg was detected in the lab blank during this analyses; however, it was less than the specified detection limit.
h The laboratory indicated that painting activities during the VOST analysis time period may have contributed to xylene contamination in the samples at levels similar to those detected in the trip and field blank. All other xylene levels may be biased slightly high.

represent VOC concentrations when natural gas only was fired. Although no chlorinated compounds were spiked in the SSM, several chlorinated VOC compounds were detected in the stack gas. In order to account for these chlorinated compounds, the feed SSM was analyzed for trace levels of chlorine. The chlorine levels ranged from <0.01 percent to 0.03 percent. These trace amounts may have resulted in the formation of chlorinated VOCs.

C.4.4 CEMs

CEMs were used to measure NO_x, CO, THC, CO_2, and O_2 emissions during the Demonstration Test. CEM data are summarized in Tables C-8 and C-9. CEM data for CO_2 and O_2 compare favorably with values obtained from Orsat analysis. These data reflect typical excess air values for a natural gas-fired furnace.

Table C-8. Summary of NOX, CO, and THC CEM Data

		Concentration (ppm - dry basis)		
Run No.	Value	NO_x	CO	THC as C_3H_8
1	Average	357	>6.1	<7.4
	Low	328	4.8	<6.9
	High	373	>54.1	8.4
2	Average	338	6.9	11.3
	Low	310	6.3	8.9
	High	423	7.4	18.2
3	Average	383	5.0	<6.4
	Low	311	4.9	<5.9
	High	435	5.2	8.1

Table C-9. Summary of CO_2 and O_2 CEM Data

		Concentration (%)	
Run No.	Value	CO_2	O_2
1	Average	9.2	4.9
	Low	8.8	4.6
	High	9.5	6.5
2	Average	8.9	4.9
	Low	8.2	4.4
	High	11.8	5.2
3	Average	9.6	4.9
	Low	9.6	4.8
	High	9.7	5.1

C.5 *Quench Water*

The quench water was tested to determine if any of the metals or semivolatile organics present in the slag or infusible matter leached into the quench water.

Concentrations of cadmium, chromium, and lead were detected and are listed in Table C-10. It appears these concentrations increased after Runs 1 and 2. Since many of the readings are close to or below analytical detection limits and method quantitation limits, the significance of these increases is minimal, however. Concentrations of semivolatiles, bismuth, and zirconium are considered insignificant, since they were at or below the analytical detection limits and method quantitation limits.

Table C-10. Quench Water from B&W SITE Demonstration

	Cadmium (μg/L)	Chromium (μg/L)	Lead (μg/L)
Before Run 0	<3.0	<7.0	<25
After Run 0	<3.0	<7.0	<25
Before Run 1	6	18	<25
After Run 1	11	26	31
Before Run 2	<3.0	<7.0	<25
After Run 2	(4)	16	41
Before Run 3	(4)	16	41
After Run 3	(4)	10	<25

Notes:
1. Values given as less than (<) a certain quantity were below the instrument detection limit; the quantity given is the detection limit.
2. Values in parentheses represent identified analytes with estimated values that are above instrument detection limits but below method quantitation limits.

Appendix D

Case Studies

D.1 Municipal Solid Waste (MSW) Ash Testing

The cyclone furnace was used in a research and development project to vitrify MSW ash containing heavy metals. The cyclone furnace produced a vitrified MSW ash which was below EPA leachability limits for all eight of the RCRA metals. The successful treatment of MSW ash suggested that the cyclone furnace could treat high-inorganic-content hazardous wastes and contaminated soils that also contain organic constituents. These types of wastes/soils exist at many Superfund sites, as well as at sites where petrochemical and chemical sludges have been disposed.

The suitability of the cyclone vitrification technology relies on the premise that for acceptable performance in treating hazardous waste mixtures containing organic and heavy metals constituents, the cyclone furnace must melt the SSM while producing a non-leachable slag. It must also achieve the DREs (currently 99.99%) for organic contaminants normally required for RCRA hazardous waste incinerators. The high temperature (over 3000°F), turbulence, and residence time in the cyclone and main furnace are expected to achieve high organics DREs.

D.2 Emerging Technologies Testing

D.2.1 Introduction

The B&W Cyclone Vitrification Furnace was initially evaluated for the treatment of heavy- metal-contaminated soil under the EPA's SITE Emerging Technologies Program. The sampling and analysis program for this test was conducted by B&W. The favorable results of that two-part study led to B&W's participation in the present Technology Demonstration Program.

The Emerging Technology tests took place during the fall of 1990 and summer of 1991. These tests were designed to evaluate whether the 4 to 6-million Btu/hr B&W cyclone furnace located at the B&W Alliance Research Center in Alliance, Ohio was capable of treating soils contaminated with heavy metals. The same pilot-scale unit was employed during this Technology Demonstration Test, with minor modifications to the feed system.

D.2.2 Phase I

The specific objectives of the first phase of Emerging Technology tests included the establishment of cyclone operability, determination of slag leachability and volume reduction, and determination of preliminary mass balance for the cyclone treatment process.

Testing utilized SSMs spiked with high levels of lead, cadmium, and chromium. These soils were fed at nominal rates of 50 and 150 lb/hr tangentially into the cyclone furnace. The soil was melted and the resulting slag was released into a water-filled slag tank where it was solidified.

In order to determine whether a vitrified material was produced, samples of the feed SSM and slag were taken and analyzed for total metals content and metals leachability using the Toxicity Characteristic Leachability Procedure (TCLP). The properties of the SSMs, the volume reductions experienced, and preliminary metals mass balances to determine the fate of the heavy metals during soil treatment were also determined.

The results of this study are summarized in the following:

Metals Leachability after Cyclone Treatment: The results indicate the vitrification process changed the physical and chemical composition of the soil in such a manner as to render the heavy metals less leachable. The percent leachability for lead, cadmium, and chromium in the untreated SSM were 29, 84, and 3.8

percent, respectively. Percent leachability of the slag for lead, cadmium, and chromium was 0.18, 2, and 0.07 percent, respectively. All slag samples were well below TCLP limits for the three heavy metals.

Total Metals in Soil and Slag: The total metals results on the soil and slag samples, averaged and reported on a dry basis, are given in Table D-1. As compared to the level of total metals in the SSM, the slag was relatively enriched in chromium and depleted in lead and cadmium.

Volume Reduction: The vitrification process achieved a volume reduction of approximately 35 percent over the dry SSM.

Table D-1. Total Metals in Soil, Slag, and Multiple Metals Train Particulates (mg/kg)

Sample	Cadmium	Chromium	Lead
Composite Soil (Dry SSM)			
11/15	1316±40	1391±86	8007±248
11/16	1223±34	1339±93	7390±214
Reagent Blank	<0.05	<0.05	<0.05
Composite Slag			
11/15	101	1907	1624
11/16	134±3.2	2169±147	2432±221
Reagent Blank	<0.05	<0.05	<0.05
Multiple Metals Train Particulates			
11/15	15146	12493	80414
11/16	14816	9893	99880
Filter Blank	15	108	149

Fate of Heavy Metals: Heavy metals could be trapped within the vitrified slag or be volatilized and leave the furnace with the flue gas. Metal volatility controls the distribution of heavy metals between the flyash and the slag. To determine the mass balance, a total heavy metals analysis was performed on the SSM, vitrified slag, and captured flyash. Chromium was determined to be the least volatile with between 80 and 95 percent retention in the slag. Cadmium was the most volatile metal, with a range of 7 to 8 percent retention in the slag. Lead fell between chromium and cadmium, in terms of slag retention, at 24 to 35 percent.

D.2.3 Phase II

The second phase of the Emerging Technology tests was designed to build upon the knowledge gained in the first phase of tests. Phase I established the suitability of the cyclone furnace for the vitrification of contaminated soils. Phase II provided additional operating data and allowed further optimization of process parameters.

Like Phase I, Phase II utilized SSMs spiked with lead, cadmium, and chromium. Feed rates in Phase II ranged from 100 to 300 pounds of SSM per hour. When the feed rate was increased to 400 pounds per hour, the furnace temperature dropped and slag tapping stopped or was blocked. The effects of feed rate on various parameters were studied. Results indicated that NO_x levels and heavy metals concentrations in the slag were proportional to feed rate, while slag temperatures were inversely proportional to feed rate.

Phase II testing included an evaluation of Borax as a fluxing agent. Fluxing agents are intended to cause the soil to melt and tap at lower temperatures, thereby decreasing metals volatilization and increasing metals capture in the slag. In a fluxing test, a mixture containing 10 percent Borax and 90 percent SSM was fed to the cyclone furnace at a nominal rate of 200 pounds per hour. The results of this Borax addition are as follows:

- Natural gas load was reduced from 5 million Btu per hour to 4.1 million Btu per hour.
- The slag temperature was reduced from 2430°F to 2320°F.
- NO_x levels in the stack decreased from between 318 and 337 ppm to 260 ppm.
- Flyash production increased.
- Metals emissions rates decreased slightly.
- TCLP results indicate that the leachability of lead from the SSM decreased slightly; further testing would be required to determine whether this change was statistically significant.
- Volume reduction, though not directly measured, appeared to decrease.
- Cadmium retention in the slag increased slightly, but further testing would be required to confirm the significance of this change.

After these results were evaluated, the developer determined that the addition of Borax did not significantly improve the operation of the cyclone furnace.

The remainder of the Phase II testing primarily reinforced the results of the Phase I testing, although Phase II testing used wet feed and Phase I testing used dry feed. Additional data from Phase II testing are summarized in the following:

- All slag samples were below TCLP limits for the three metals.

- The percent leachabilities for lead, cadmium, and chromium in the untreated SSM were 20, 57, and 0.55 percent, respectively. The percent leachabilities for lead, cadmium, and chromium in the slag were 0.09, 0.70, and 0.02 percent, respectively.

- As compared to the feed SSM, the slag was relatively enriched in chromium and depleted in lead and cadmium.

- The vitrification process achieved a volume reduction of approximately 25 percent between the SSM and the slag. This is somewhat lower than the 35 percent volume reduction achieved in Phase I, but the difference may simply reflect the difficulty of obtaining representative samples of the slag.

- As in Phase I, heavy metals were retained in the slag or were volatilized into the flue gas. In Phase II testing, the following percentages of heavy metals were retained in the slag:

Chromium:	78 to 95 percent
Lead:	38 to 54 percent
Cadmium:	12 to 23 percent

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